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EARTHQUAKE DAMAGE TO UNDERGROUND FACILITIES

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ABSTRACT

The potential seismic risk for an underground nuclear waste repository will be one of the considerations in evaluating its ultimate location. However, the risk to subsurface facilities cannot be judged by applying intensity ratings derived from the surface effects of an earthquake. It is common knowledge in mining circles that the damage caused by an earthquake is significantly less in the subsurface than it is at the surface; mines have operated for a substantial period of time in some of the most seismically active regions of the world.

If the smaller damage effects of earthquakes in the subsurface are to be used in assessing the hazard to an underground nuclear waste repository, then a quantitative data base is needed to replace the general precept that earthquake damage is minimal to nonexistent in the subsurface. The purpose of this study was to develop such a quantitative data base.

A literature review and analysis were performed to document the damage and non-damage due to earthquakes to underground facilities. Damage from earthquakes to tunnels, mines, and wells and damage (rock bursts) from mining operations were investigated. Damage from documented nuclear events was also included in the study where applicable.

Principal conclusions developed in this study are:

- There are very few data on damage in the subsurface due to earthquakes. This fact itself attests to the lessened effect of earthquakes in the subsurface because mines exist in areas where strong earthquakes have done extensive surface damage.
- More damage is reported in shallow tunnels near the surface than in deep mines.
- In mines and tunnels, large displacements occur primarily along pre-existing faults and fractures or at the surface entrance to these facilities.
- Data indicate vertical structures such as wells and shafts are less susceptible to damage than surface facilities.
- More analysis is required before seismic criteria can be formulated for the siting of a nuclear waste repository.

PREFACE

The National Waste Terminal Storage Program was initiated to conduct the research to select a site for the disposal of high-level radioactive waste in deep geologic formations. As part of this program, the Savannah River Laboratory is conducting geologic research that is particularly relevant to potential repository sites in the Southeast and of generic applicability. One generic study in this program is concerned with earthquake damage to a repository in a geologic media. Part of this study was conducted by Terra Tek under contract to the Savannah River Laboratory. This report presents the results of the first phase of the study.

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EARTHQUAKE DAMAGE TO UNDERGROUND FACILITIES

INTRODUCTION

The potential seismic risk for an underground nuclear waste repository is considered in evaluating the ultimate location of the facility. The possible damage resulting from either large-scale displacements or high accelerations should be considered in evaluating a potential site. Current concepts envision a repository sited in one or more of a variety of geologic media at depths ranging from 500 to 1500 meters (m). The geologic media being considered include salt, shale (argillite), and crystalline rock. Independent geologic studies are being conducted to assess the feasibility of siting a repository in these media in the continental United States.

Scattered through the available literature are statements to the effect that below a few hundred meters shaking and damage in mines are less than at the surface; however, data for decreased damage underground have not been completely reported and explained.

In order to assess the seismic risk for an underground repository, a data base must be established and analyzed to evaluate the potential for seismic disturbance. To develop this data base, a search of the literature was made to document the damage or non-damage to underground facilities due to earthquakes and to evaluate the significance of these data. A number of reports listed damage from earthquakes to underground structure such as mines and tunnels, but these were primarily of a qualitative nature. Displacements associated with four major earthquakes in several parts of the world were documented in 1959.[1] More recently, the effect of earthquakes on shallow tunnels, primarily in the United States, has been collected and analyzed.[2,3] In addition to these data, a large number of individual reports have indicated both damage and non-damage resulting from earthquakes of magnitudes greater than 5.[4-8]

In addition to these data, other sources of potential information were investigated. These include:

- More complete and recent data from foreign sources in earthquake prone areas such as Japan.
- Data from mining operations where earthquakes are initiated by the mining process. (These needed to be evaluated in terms of the potential damage from equivalent far-field earthquakes.)

- Results from the nuclear events at the Nevada Test Site and the Alaskan Test Site as well as Plowshare experiments. These tests provide the most quantitative data in the near-field environment. These tests were well instrumented and may assist in evaluating and establishing damage criteria with respect to the seismic spectrum resulting from an earthquake.

Recent technical interchange with the Chinese, Russians, and Japanese has increased our data base significantly with respect to methods for earthquake prediction and the damage resulting from destructive earthquakes. These foreign groups were contacted as well as the United States geologists (Raleigh and Brace) who have made recent trips to these countries. Also the cognizant groups in Asia, Europe, and South America were contacted for pertinent information. It was the aim of the study to gather as large a data base as possible because of the relatively infrequent occurrence of large earthquakes in any one country.

Data on mines and mining operations were collected from government agencies (U. S. Geological Survey, U. S. Bureau of Mines, California Division of Mines and Geology, etc.). Personnel in those agencies were contacted for published data and individual discussion.

Nuclear events provided a quantitative data base for the near-field effects in region of large displacements and high acceleration. Nuclear events like BOXCAR, BENHAM, MILROW, and CANNIKIN were greater than one megaton (>1 Mt), equivalent to a magnitude of ~6.5 earthquake.[9-11] Scaled ground motion data from a number of these sources may provide part of the empirical basis to establish a damage criteria for a waste repository.

BACKGROUND

The focus, or hypocenter, of an earthquake is the source of the waves that form the earthquake. The depth of focus is the depth of the source below the surface.

Earthquakes are classified by depth of focus as follows:

Shallow	0- 70 km
Intermediate	70-300 km
Deep	300-700 km

The epicenter is the point on the earth's surface above the focus of the earthquake.

The magnitude of an earthquake is a measure of ground motion recorded at a seismic station. The term was originally defined by Richter (1935)[12] to facilitate comparison of the amount of energy released in earthquakes. Richter's original work was done with data from shallow earthquakes in southern California and adjoining states.

Richter[12] defined local magnitude (M_L) as the logarithm (base 10) of the largest amplitude measured in microns (0.001 mm) on the record made by a standard Wood-Anderson torsion seismometer (period = 8.0 seconds, magnification = 2800, and damping factor = 0.8) at a distance of 100 km from the epicenter of the earthquake. The magnitude of an earthquake recorded at other distances can be determined if it is known how the largest amplitude varies with distance.

Gutenberg and Richter[12,13] investigated the relation between the energy released by an earthquake and its magnitude and found that

$$\log_{10} E = 5.8 + 2.4m$$

and since the body-wave magnitude $m = 2.5 + 0.63M$, this is equivalent to

$$\log_{10} E = 11.4 + 1.5M$$

where E = total energy released by an earthquake in ergs, and M = magnitude of an earthquake determined from surface waves.

The intensity of an earthquake is the amount of shaking, damage to property, and earth deformation felt or observed at a given place. Intensity is measured in terms of arbitrarily defined scales. The most widely used intensity scale is the Modified Mercalli (MM) scale shown in Table 1.[14] Richter[15] points out that the intensity of an earthquake does not represent a measurement, but a rating, developed by a practiced observer, from reports given by the public. Intensity has been correlated roughly with magnitude by the relationship,

$$M = 1 + \frac{2}{3} I_o$$

however, this implies that the intensity is a true numerical quantity which in fact it is not.

TABLE 1

Earthquake Measurements — Modified Mercalli Intensity Scale (1956 Version)[a]

Intensity, MM	*Description*
I	Not felt. Marginal and long-period effects of large earthquakes.
II	Felt by persons at rest, on upper floors, or favorably placed. Average ground motion, 0.23% g; ground motion range, 0.1 to 0.5% g.
III	Felt indoors. Hanging objects swing. Vibration; like passing of light trucks. Duration estimated. May not be recognized as an earthquake. Average ground motion, 0.31% g; ground motion range, 0.1 to 0.8% g.
IV	Hanging objects swing. Vibration; like passing of heavy trucks, or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV, wooden walls and frame creak. Average ground motion, 0.93% g; ground motion range, 0.2 to 4.6% g.
V	Felt outdoors, direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters and pictures move. Pendulum clocks stop, start, change rate. Average ground motion, 1.33% g; ground motion range, 0.2 to 7.5% g.
VI	Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knick-knacks, books, etc., fall off shelves. Pictures fall off walls. Furniture moved or overturned. Weak plaster and masonry D crack. Small bells ring (church, school). Trees, bushes shaken (visibly, or heard to rustle). Average ground motion, 4.0% g; ground motion range, 0.5 to 17.5% g.
VII	Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices (also unbraced parapets and architectural ornaments). Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving-in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged. Average ground motion, 6.7% g; ground motion range, 1.8 to 14% g.

a. Ground motion accelerations taken from Reference 14.

TABLE 1 (Continued)

Intensity, MM	*Description*
VIII	Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes. Average ground motion, 17.2% g; ground motion range, 5.1 to 35% g.
IX	General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged (general damage to foundations). Frame structures, if not bolted, shifted off foundations. Frames cracked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas, sand and mud ejected, earthquake fountains, sand craters. Average ground motion, 25% g.
X	Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.
XI	Rails bent greatly. Underground pipelines completely out of service.
XII	Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

Masonry A	Good workmanship, mortar, and design; reinforced, especially laterally, and bound together by using steel, concrete, etc., designed to resist lateral forces.
Masonry B	Good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces.
Masonry C	Ordinary workmanship and mortar; extreme weaknesses, such as failing to tie in at corners. Neither reinforced nor designed against horizontal forces.
Masonry D	Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.

Earthquake risk maps (Figure 1) have been formulated for the United States based on historical damage to various areas.[16,17] This map is directly correlative with maps showing the location of major earthquakes (intensity 5 or greater) up through 1970 (Figure 2).[18] This correlation is due to the fact that the risk map was developed from surface damage associated with historic seismicity; however, how the risk map applies to underground facilities is not yet known.

The resulting velocity, acceleration, and displacement spectra from an earthquake are usually plotted as a function of frequency (period) on a pseudo-velocity diagram. These plots are helpful in evaluating and designing surface structures. Figure 3 shows a plot of site-independent spectra from several sources.[19]

Relationships of surface acceleration (Figure 4)[4] and velocity (Figure 5)[20] have been established as a function of intensity and magnitude with distance. The relationships between predominant period and magnitude are shown as a function of distance (Figure 6).[19]

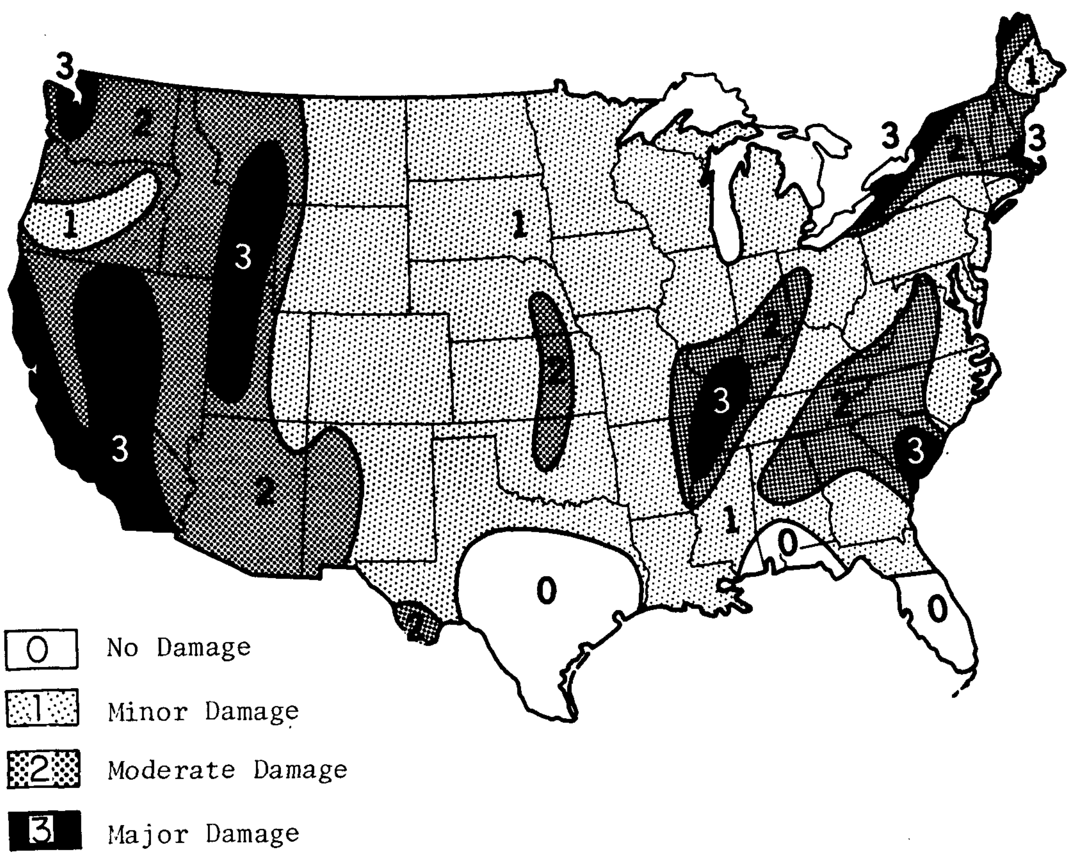

FIGURE 1. Risk of Damage from Earthquakes in the United States[16]

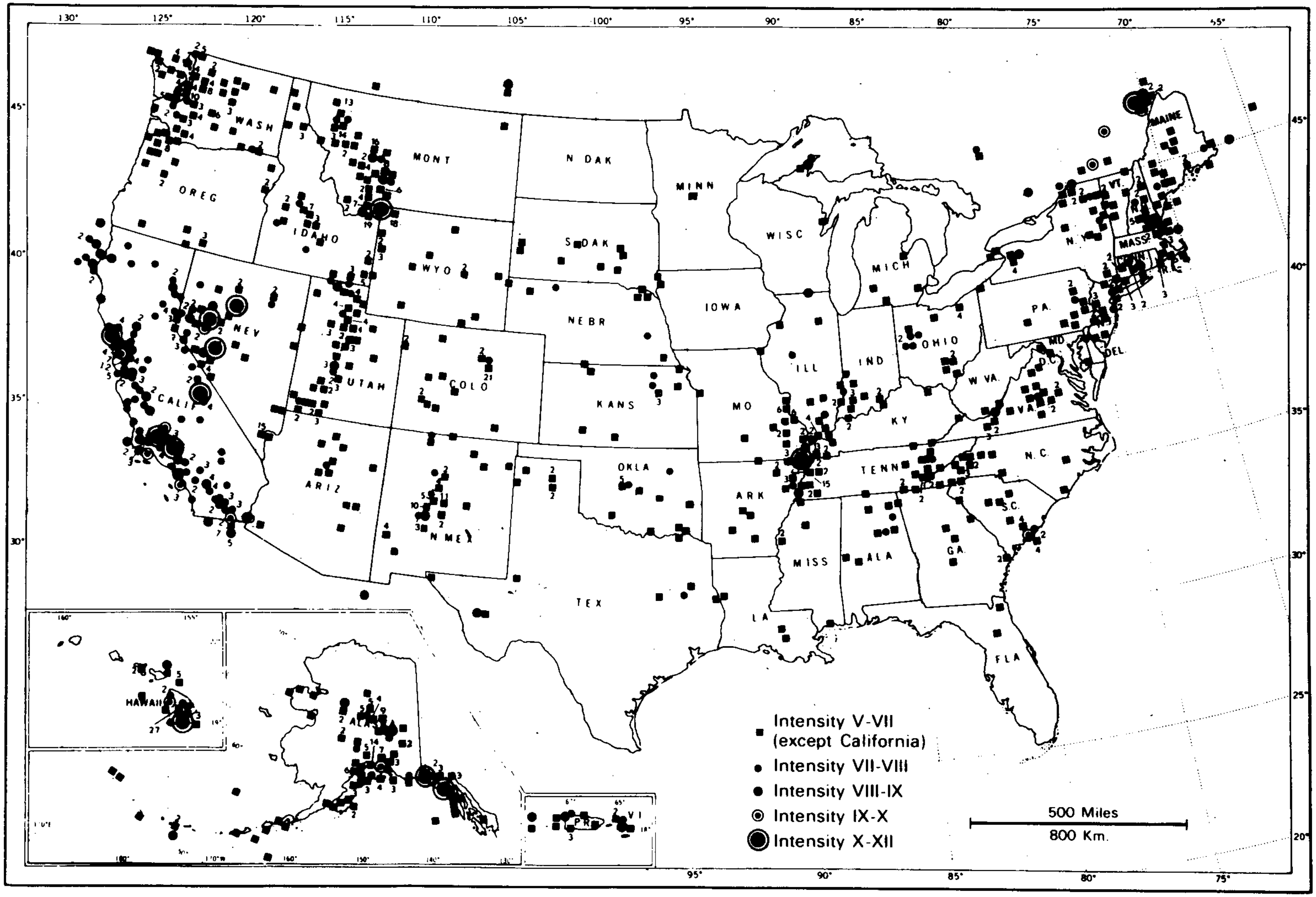

FIGURE 2. Earthquakes (Intensity V and Above) in the United States Through 1970[18]

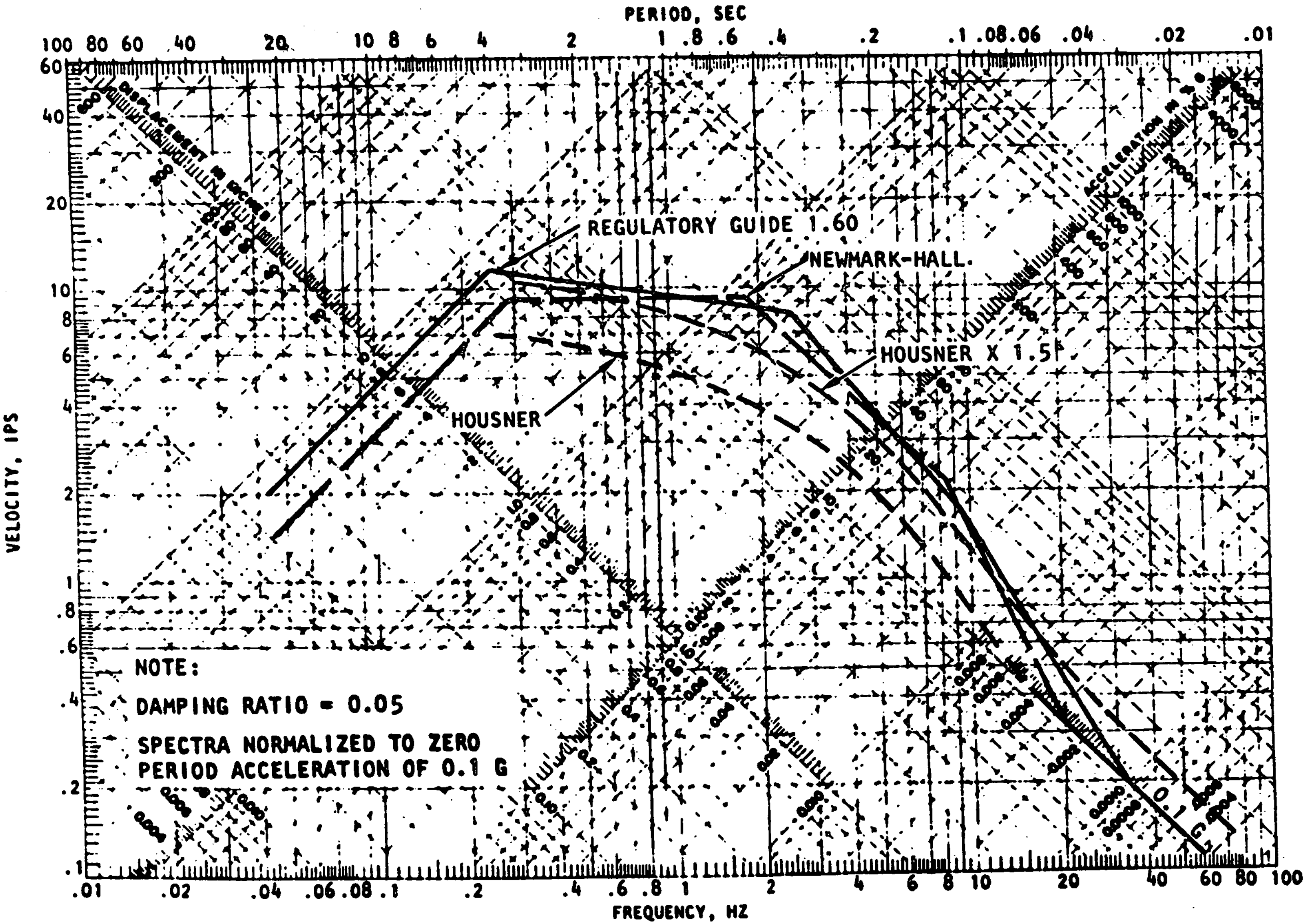

FIGURE 3. Comparison of Site-Independent Spectra[19]

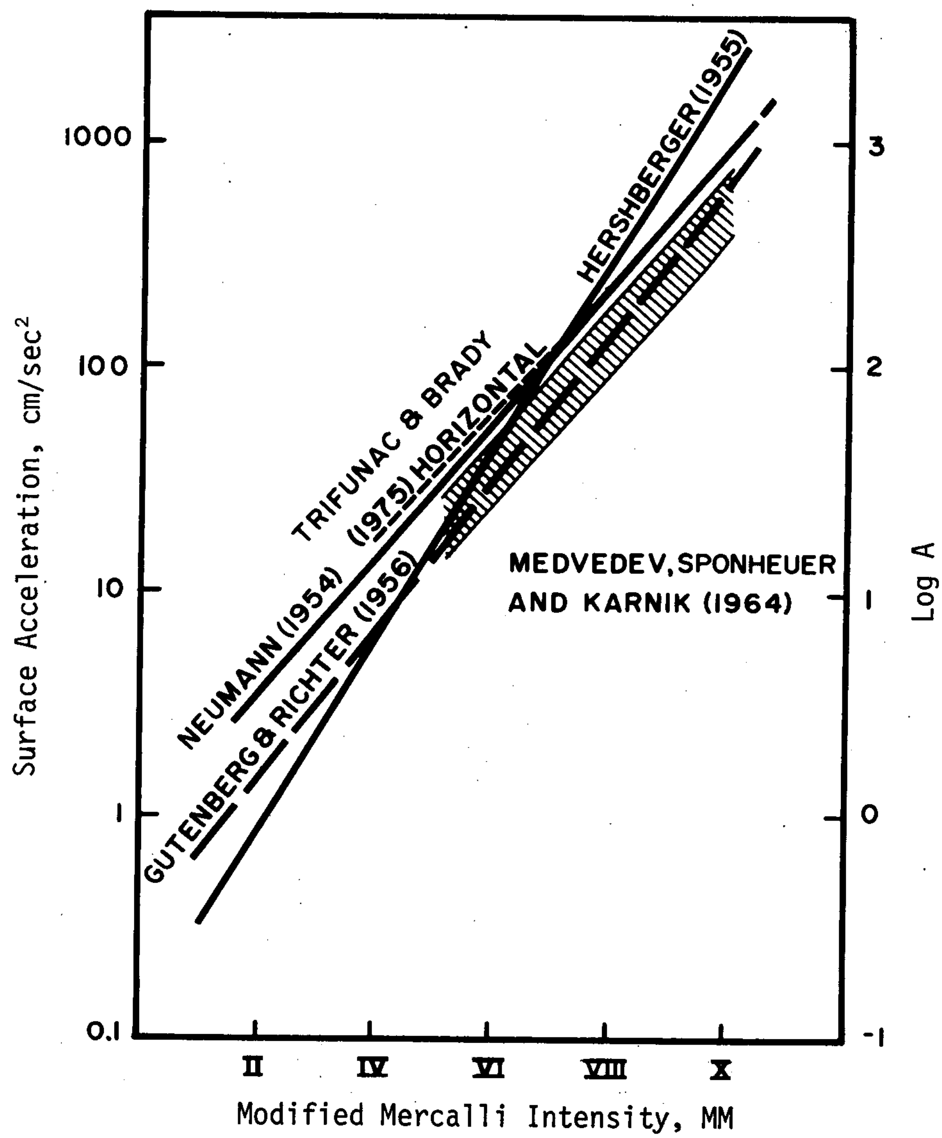

FIGURE 4. Surface Acceleration Versus Intensity[2]

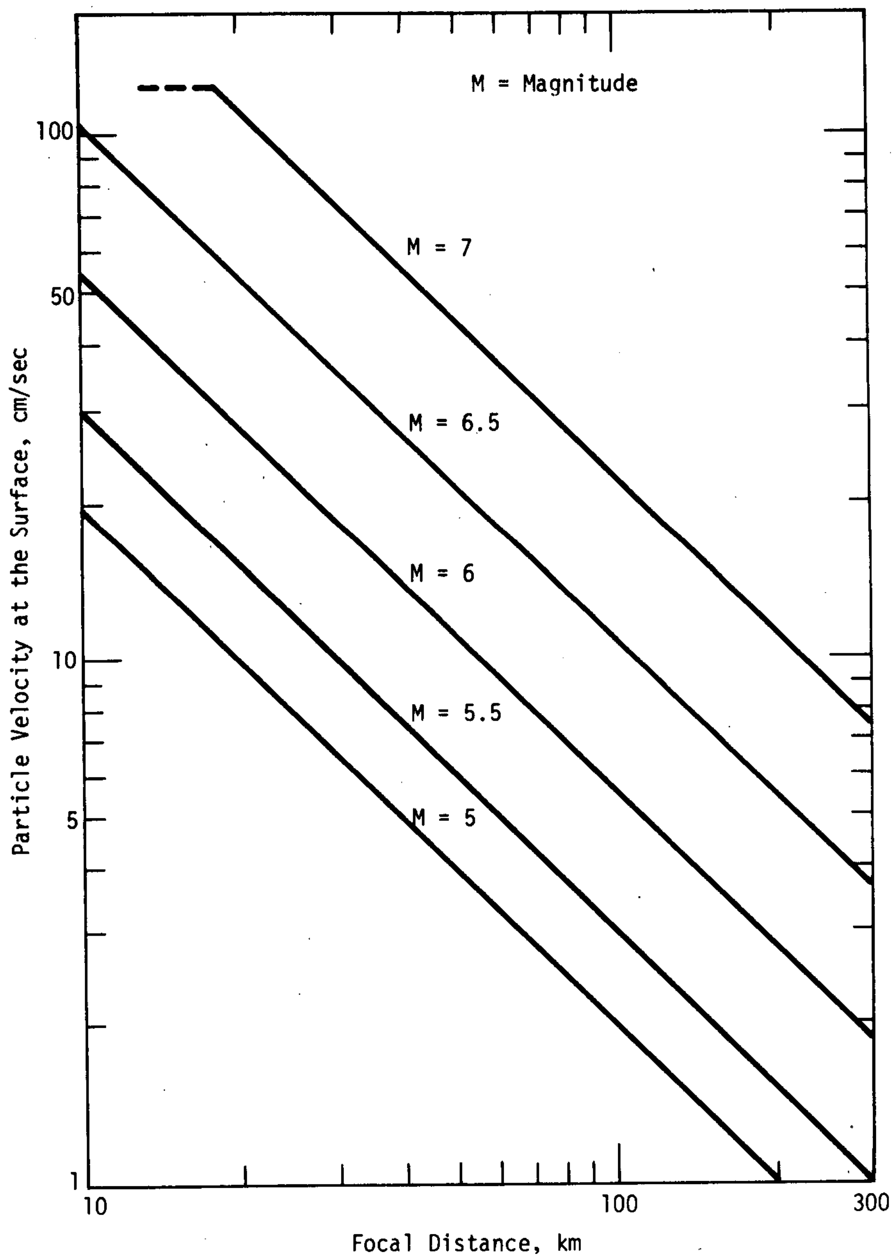

FIGURE 5. Maximum Probable Ground Velocities[20]

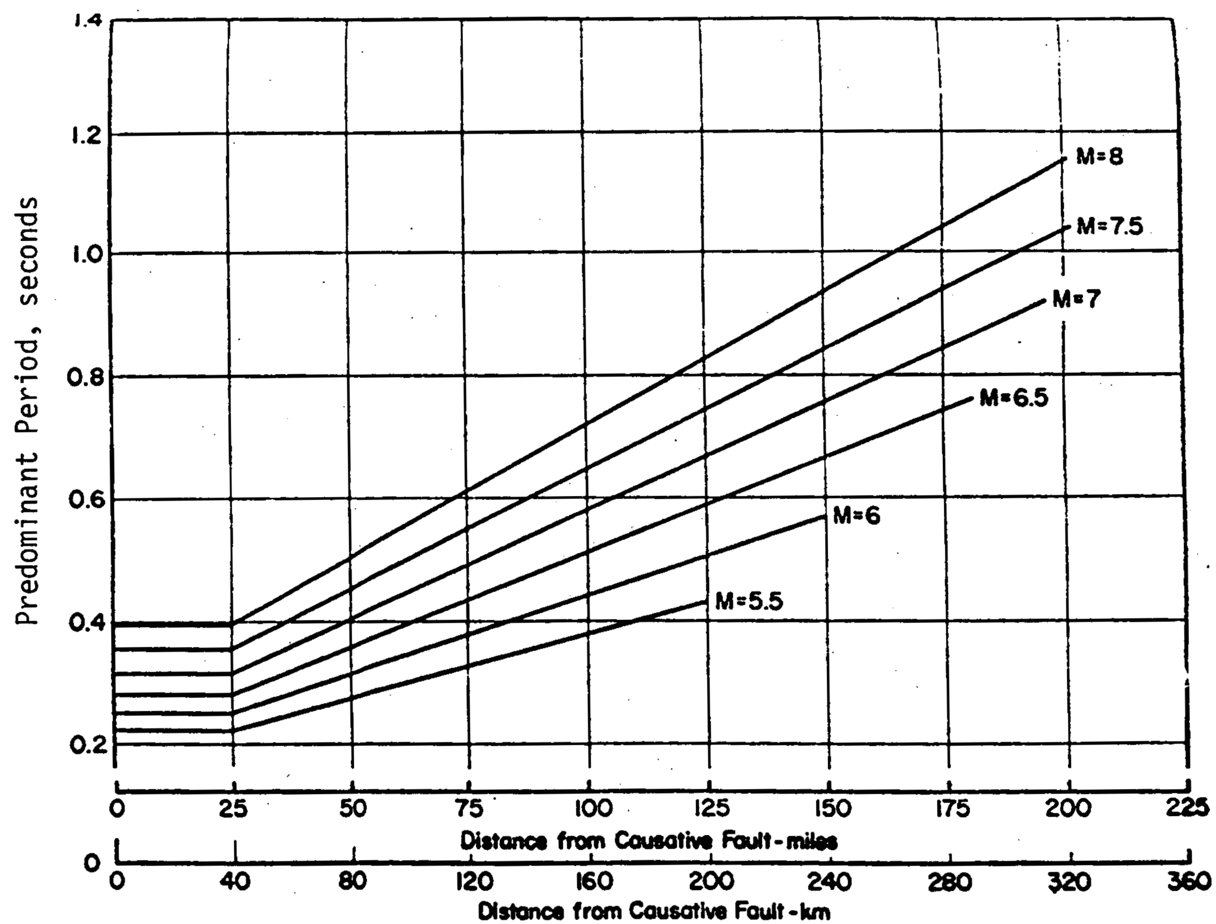

FIGURE 6. Predominant Periods for Maximum Acceleration in Rock[19]

EXISTING DATA BASE ON EARTHQUAKE DAMAGE

Tunnels and Shallow Underground Openings

Data on the seismic stability and behavior of shallow underground openings are very well summarized in a thesis by Rozen[2] and in a paper by Dowding.[3] Observations from 71 tunnels responding to earthquake motions were compared. Dynamic behavior was compared with intensity and magnitude as a function of distance. The cases which are discussed in detail in Rozen's thesis are given in Appendix A. The studies compared calculated accelerations at the ground surface with tunnel damage and show that the tunnels are less susceptible to damage than surface structures or facilities. Peak accelerations at the surface of less than 0.2 g did not damage the tunnels; between 0.2 and 0.5 g's, damage was only minor; and damage was significant only above 0.5 g (Figure 7).[2,3] Most of the damage that occurred was located near a portal. Richter magnitude as well as Modified Mercalli intensity is correlated with acceleration for various cases in Figure 8.[2,3] Large accelerations are correlative with large magnitudes and high intensities. At any one specific site, calculations of accelerations were based upon the earthquake magnitude and the epicentral distance through attenuation laws developed by McGuire[21] and shown in Figure 9.[2,3] The calculated peak acceleration, velocity, and displacement levels given in Appendix A are at surface, and no reduction was made for attenuation with depth. Rozen[2] correlated peak surface motion and related intensity levels with observed underground damage.

Variation and attenuation of peak surface accelerations with distance show the relatively large spread depending on the model and the data base used (Figure 9).[2,3] The variation in attenuation is further complicated because of the variety of geologic environments from which the data were gathered. The peak velocity attenuation is also a function of focal distance (Figure 10).[2] The attenuation curves of Seed[22] for a wide range of earthquake magnitudes do not show a great deal of difference between rock and alluvium. But the results in rock at 300-m depth by Kanai[23] indicate that initial peak velocities are lower by a factor of ~2 at depth. More detailed acceleration attenuation curves from a variety of sources are given in Figure 11.[2]

The data of Rozen[2] summarized in the work by Dowding[3] indicate that: (1) experience shows that tunnels are more stable than structures located on the surface; (2) critical frequencies are lower for large underground chambers than tunnels because of the increase in the size of underground chambers; and (3) if the rock mass is considered continuous, the resonant circulation of surface waves in the larger chambers cannot occur at frequencies below 100 Hz.

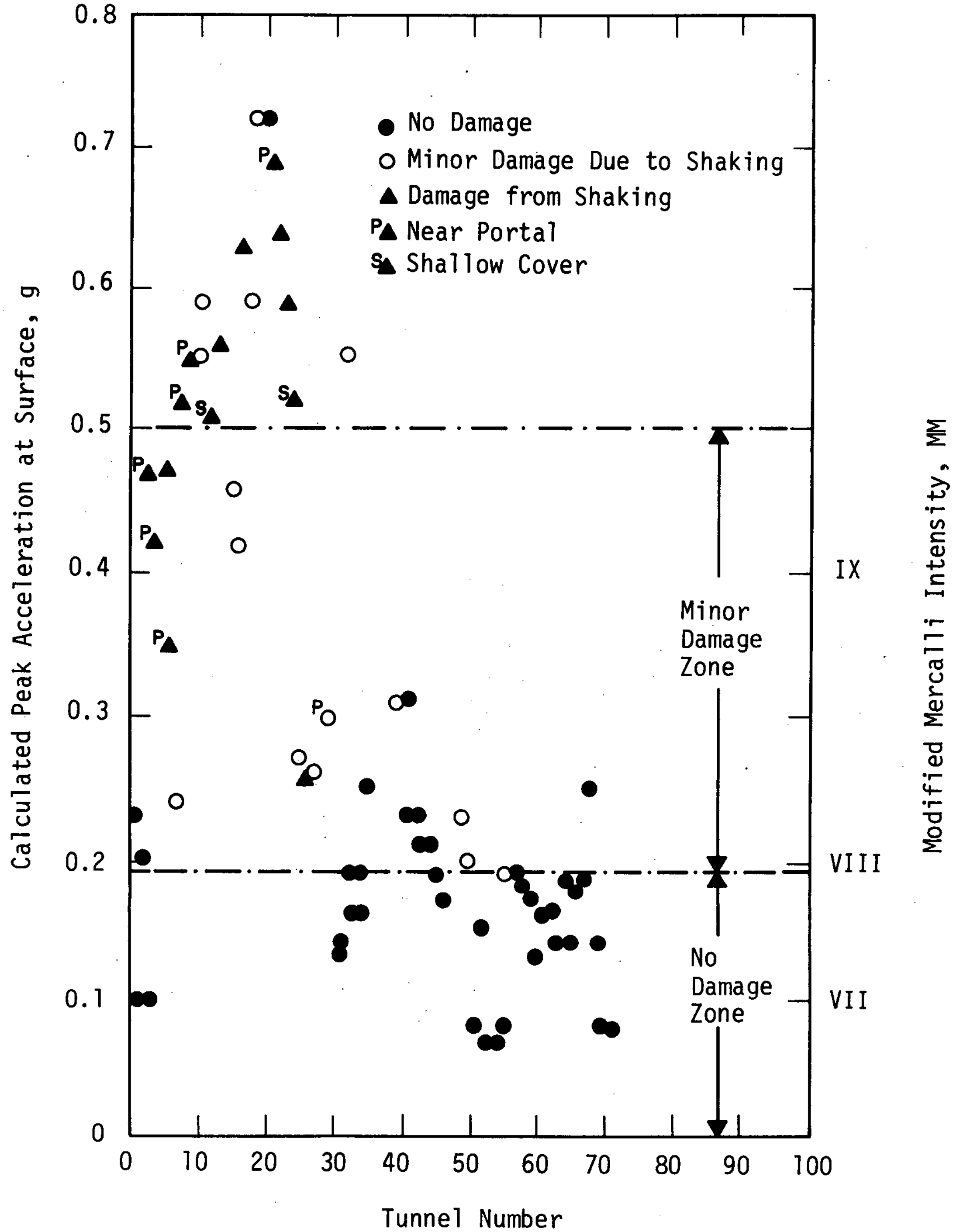

FIGURE 7. Calculated Peak Acceleration at the Surface and Associated Tunnel Damage[2,3]

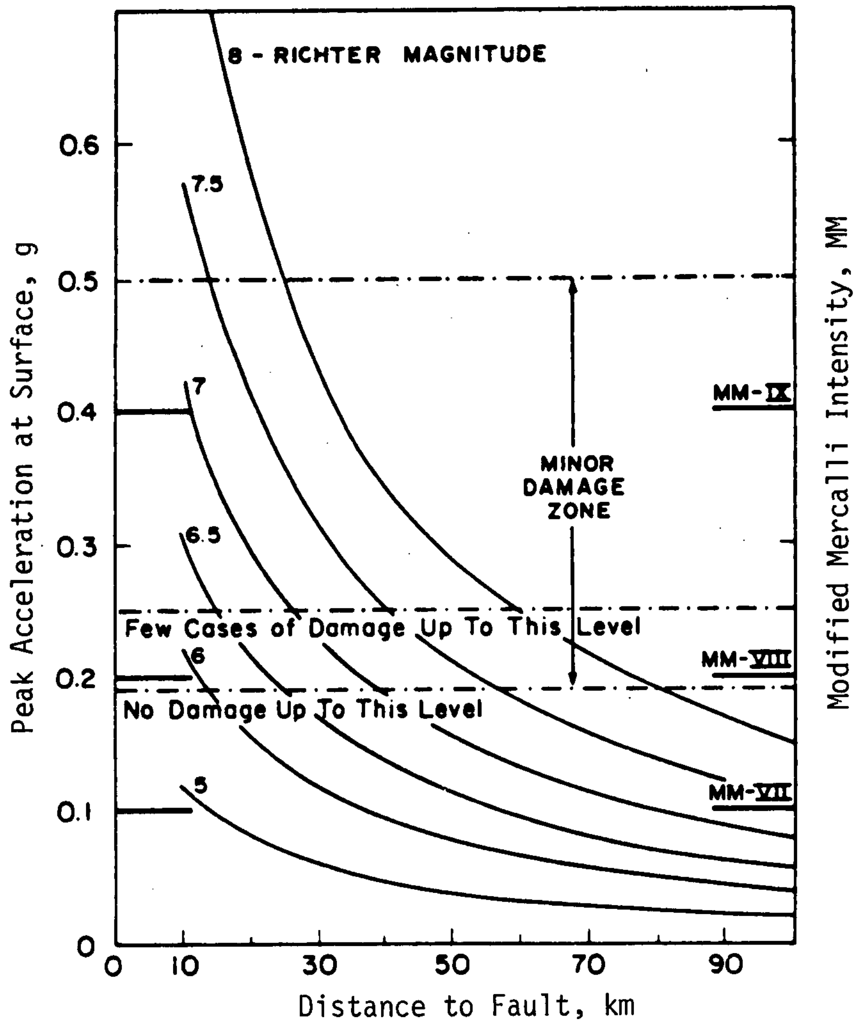

FIGURE 8. Accelerations, Modified Mercalli Intensity, and Associated Tunnel Damage[2,3]

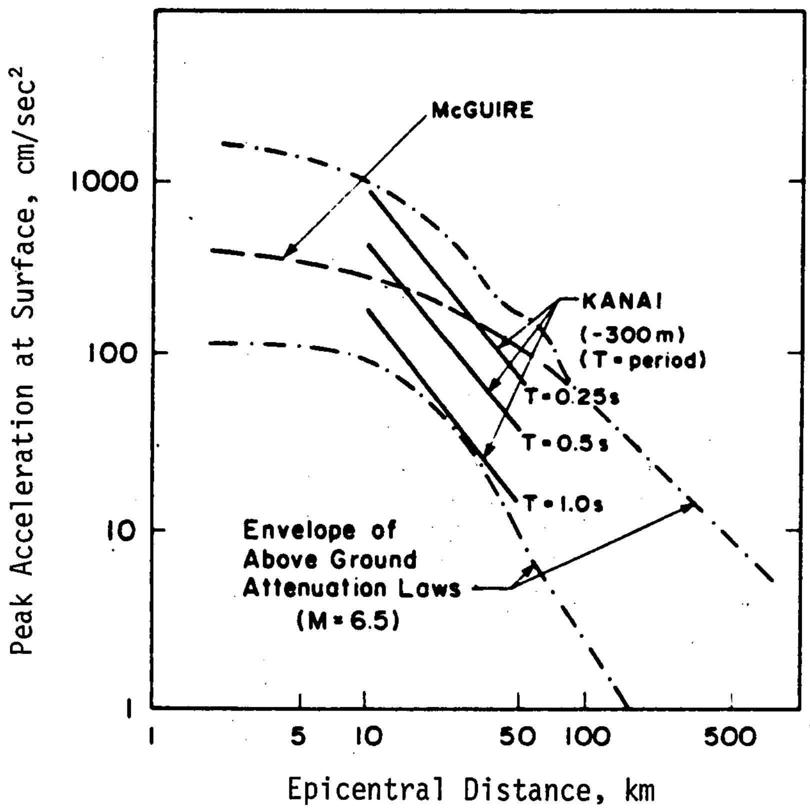

FIGURE 9. Spread of Attenuation Relationships for Magnitude 6.5 Earthquake[2,3]

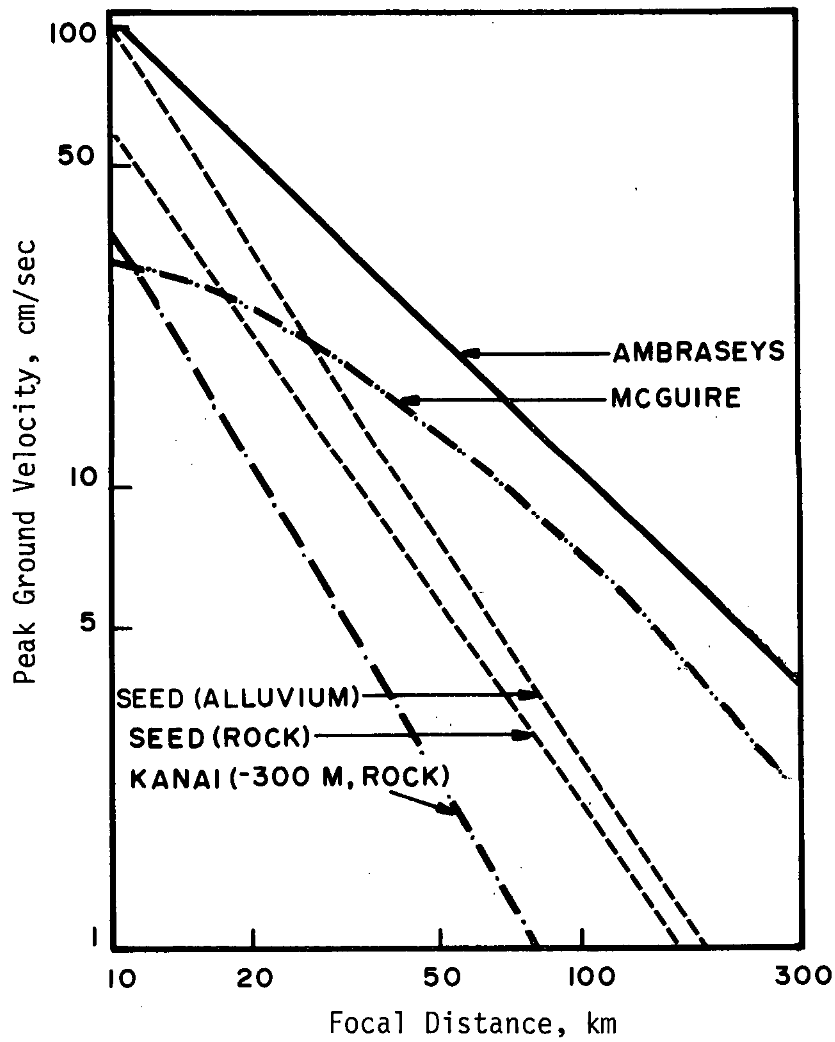

FIGURE 10. Velocity as a Function of Focal Distance for Various Site Conditions[2]

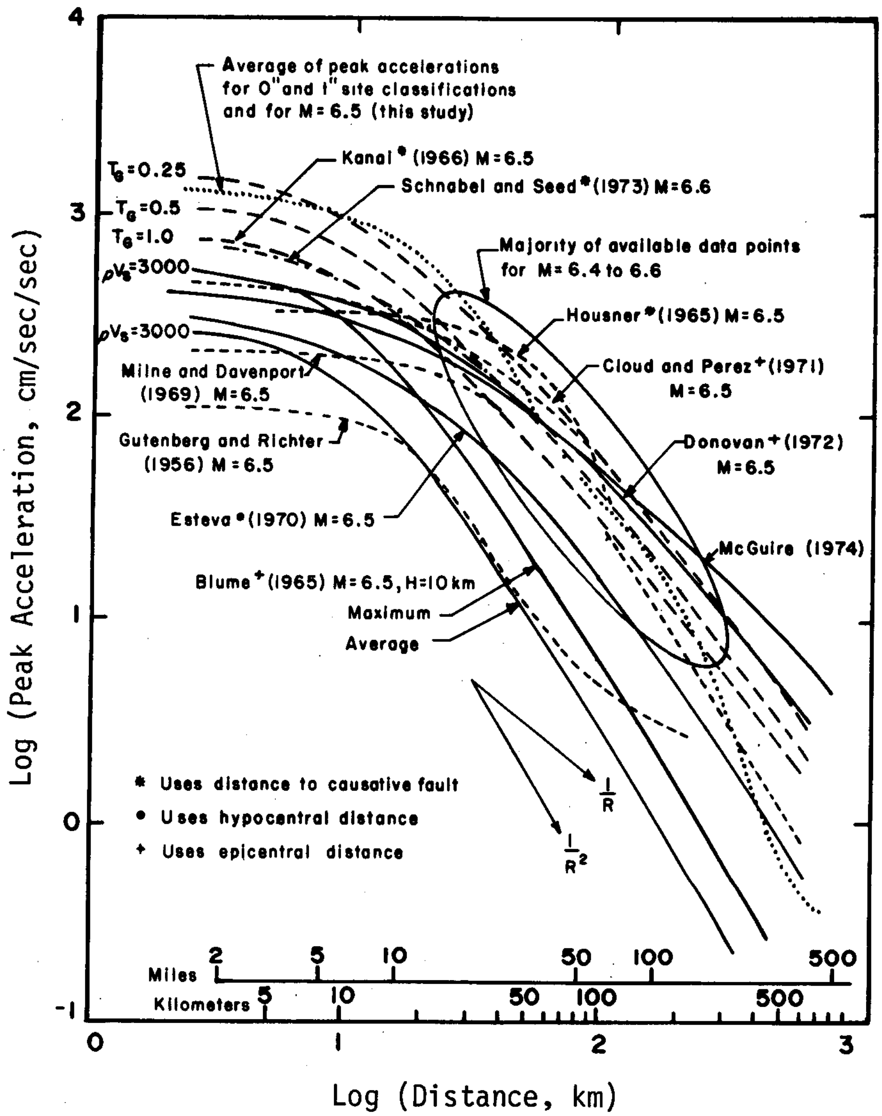

FIGURE 11. Various Relationships Between Peak Acceleration and Distance from Source for Magnitude 6.5 Earthquakes[2]

The conceptual designs of a waste repository indicate that its configuration will probably be ~10 meters, rather than 100, in diameter; hence, the following conclusions are: (1) critical frequencies calculated from Rozen's data[2] for underground openings of this size are ~150 Hz, and, therefore, threshold damage would not occur unless the repository was relatively close to the epicenter; (2) peak motions may be selectively amplified on a frequency basis; (3) the dynamic stress concentrations are probably no more than 20% greater than those caused by the opening; and (4) perhaps most importantly, that the primary cause of failure of these underground excavations is relative movement along pre-existing faults, or at the portal of the tunnel which is located at ground surface.

Duke and Leeds[1] reviewed information on tunnel damage as well as some mine damage due to earthquakes and drew the following conclusions.

- Severe tunnel damage appears to be inevitable when the tunnel is crossed by a fault or fault fissure which slips during the earthquake.
- In tunnels away from fault breaks, severe damage may be done by shaking to linings and portals and to the surrounding rock, for tunnels in the epicentral region of strong earthquakes, where construction is of marginal quality. Substantial reinforced-concrete lining has proved superior to plain concrete, masonry, brick, and timber in this regard.
- Tunnels outside the epicentral region and well-constructed tunnels in this region but away from fault breaks can be expected to suffer little or no damage in strong earthquakes.
- Although it would seem reasonable that competence of the surrounding rock would reduce the likelihood of damage due to shaking, inadequate comparative evidence is available on this point.
- Within the usual range of destructive earthquake periods, intensity of shaking below ground is less severe than on the surface.

The following tunnel data are the major examples of damage reported by Duke and Leeds.[1]

San Francisco Earthquake, 1906

In the San Francisco earthquake of 1906, the Wright's number 1 and number 2 tunnels on the narrow gage Southern Pacific Railroad were damaged. The 1863-m long number 1 tunnel, located in the Santa Cruz Mountains at a depth of 214 m, was offset 1.37-m transverse horizontal where it crossed the San Andreas fault. Other damage included the caving of rocks from the roof and sides, the breaking of upright timbers, the heaving upward of rails, and the breaking of ties. The second tunnel, directly south, near Glenwood, was 1737 m long and 207 m deep. It did not cross the fault and was less damaged; timbers were broken and the roof caved, blocking the tunnel at several points.[24,25] Other tunnels in the same area were undamaged.

Tokyo Area, 1923

Damage occurred to 25 tunnels close to the epicenter. This damage was attributed to shaking and not to fault movement. However, the construction, character of rock, length, and other features of the tunnels varied widely. Beyond the isoseismal corresponding to approximately 50% of the houses collapsed, tunnel damage apparently was insignificant.

Japan Earthquake, 1930

The Tanna tunnel was under construction at the time of the earthquake. A transverse offset of 2.3 m was recorded along a fault in one of the drain tunnels which extended ahead of the main tunnel heading. The only damage to the main tunnel was a few cracks in the walls. The depth was ~160 m; accelerations were not available, but 55% of the houses were destroyed at the surface above. The basin was composed of unconsolidated materials to ~40 m. The rock at a depth of 140 m was volcanic andesite. Fault displacements at the surface were less than the 2.3 m that was measured in the drain tunnel, but this may have been because movement was diffuse in the unconsolidated material near the surface.

Kern County Earthquake, 1952

Kern County, California earthquake of 1952 damaged four tunnels on the Southern Pacific railroad near Tehachapi. This was a region of large ground fractures with movement along the White Wolf fault. This is another case where the subsurface damage was greater than that on the surface. These tunnels were in the epicentral region, but the extensive damage was attributed to their location in the fault zone where displacements exceeded those at the surface.[26,27,28]

In 1966, a resurvey of the Claremont Water tunnel near Berkeley, California revealed three cracks in the tunnel at its intersection with the Hayward fault zone, which were not present when the tunnel was surveyed in 1950.[29] The tunnel is ~46 m beneath the surface at this point and shows right lateral offset of 168 mm since its construction. Of this amount, only 48 mm could be accounted for as displacement due to fracture of the lining. The remaining 119 mm is accounted for as flexure of the lining. The offset takes place in a segment of the tunnel <30 m in length. Displacement of the tunnel is not known to be associated with any seismic event, and except for buckling of the invert in the zone of fracture, no indication of vertical displacement is found. Because of this, the displacement probably reflects gradual creep along the fault zone.

Duke and Leeds[1] report that with the exception of damage caused by the 1906 and 1952 earthquakes, as reported above, no other reports of tunnel damage were discovered after reviewing over 215 tunnels in California including one that crosses the San Andreas fault. They conclude that this experience is significant because severe earthquakes occurred in 1915 (Imperial Valley), 1925 (Santa Barbara), 1933 (Long Beach), 1940 (El Centro), and 1954 (western Nevada).

Mines or Other Deep Structures

The damage from earthquakes to underground mines has been documented in several places. Reports have generally been qualitative in nature and recounted from incidents in which damage has been assessed either by those working in the mine or by people that have visited the mines subsequent to the earthquake. Quantitative data have been much more difficult to obtain and come primarily from a few sources. Most of these data are in the form of displacements or accelerations noted in mines in Japan, South Africa, and/or the United States. Recent Japanese data were obtained from Nishimatsu.[30]

The earlier Japanese work has been summarized by Duke and Leeds.[1] Several Japanese investigators measured earthquake motion at depth and simultaneously at the surface. Nasu[31] determined the ratio of displacement due to earthquakes at the surface and in tunnels at depths of up to 160 m. One of the most striking was the 2.3-m transverse horizontal offset 0.6 m beyond a tunnel heading during the 1930 Tanna earthquake. Surface/depth displacement ratios were 4.2, 1.5, and 1.2 for periods of 0.3, 1.2, and 4 seconds, respectively. The geology consisted of lake deposits at the surface and volcanic andesite and agglomerates at 160-m depth. Nasu concluded that underground motion may be four times less than at the surface.

Kanai[32-34] measured accelerations at depths up to 600 m in a copper mine in Paleozoic rock in Hitachi, but unfortunately recorded data were from small earthquakes. The ratio of surface maximum displacement to that at 300-m depth was about 6:1 at the mine and about 10:1 on the surface at a school ~6 km away on alluvium. Many earthquakes occurred where the ratio of surface to subsurface displacements were three times the above ratios. Displacements in these cases were exceedingly small because of the small nature of the earthquake measured. Kanai suggested the following attenuation laws with depth to 300 m as equations of the best fit curve to the data.

$$d = T \times 10^{0.61M - 1.73 \log R - 1.47}$$

$$v = 2\pi \times 10^{0.61M - 1.73 \log R - 1.47}$$

$$a = \frac{(2\pi)^2}{T} 10^{0.61M - 1.73 \log R - 1.47}$$

where

d = displacement, cm

v = velocity, cm/sec

a = acceleration, cm/sec^2

T = period of the wave

M = magnitude

R = distance from the earthquake

Okamoto[35] also measured acceleration both at the surface and at depth. Acceleration records from the surface and at 38 m show the marked decrease in amplitude with depth (Figure 12).[36] Based on his findings, he suggested an attenuation law to 67 m in tuff.

$$\log_{10} \frac{a_{max}}{640} = \frac{R+40}{100} (-7.604 + 1.724M - 0.1036M^2)$$

The Japanese observations indicate:

- For short periods, surface displacements are greater than underground displacements.
- The ratios of surface to underground displacements (to depths of 600 m) were dependent on surface geology, with a ratio of 10:1 in alluvium at the surface.
- For long period waves, greater than one second, the ratio of surface to underground displacement approaches unity as period increases.
- These data indicate that for a particular geology, a certain average period of a seismic wave produces a maximum surface-to-underground displacement ratio.

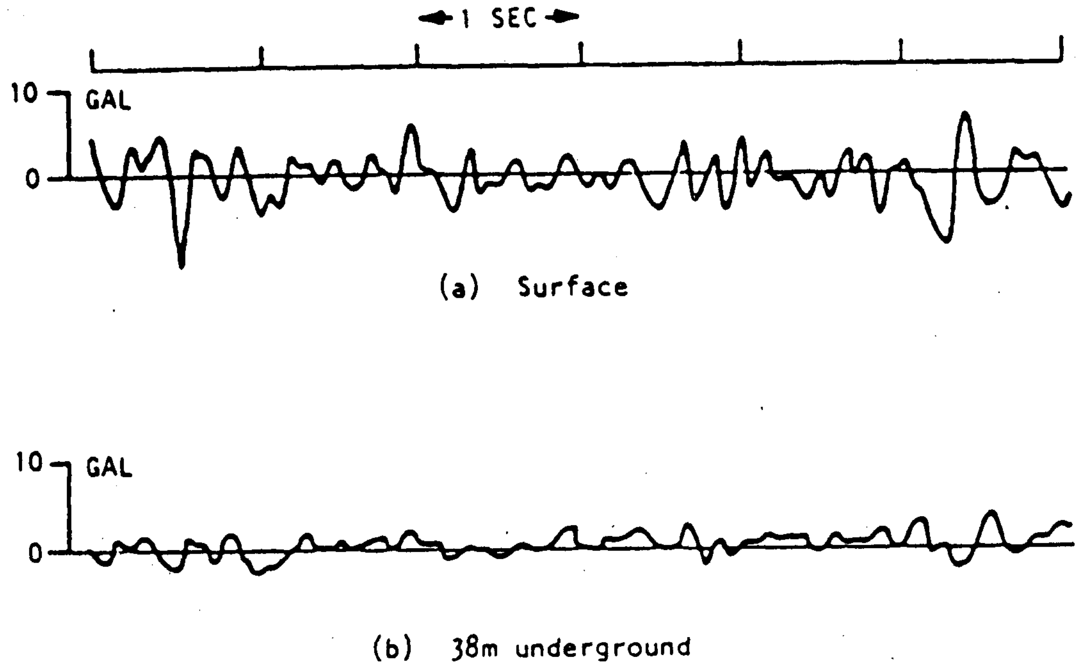

FIGURE 12. Acceleration Records Taken on the Surface and 38 m Underground at Sudagai, Northern Gumma Perfecture, Japan[35]

Carder[36] reported that for the measurements made on the surface and at 1524-m depth at the Homestake Mine, microseismic events had periods of 4 to 5 seconds. In later studies, P-waves of one second were recorded at the 91-m depth in the Homestake Mine with twice the amplitude of that recorded at a 1524-m depth. Recent studies by Brady[37] have indicated that seismic activity is noted prior to rock bursts, and some of these rock bursts have magnitudes of 3 to 4. Damage has been significant in a few of these cases. These small mining-related earthquakes fit a fault length precursor time plot at the lower end of the spectrum (Figure 13).[37] At the upper end of the spectrum are the large earthquakes at Niigata, Japan, San Fernando, California, and several locations in the U.S.S.R.

Information on earthquake damage from South Africa was obtained during discussions with U.S. Geological Survey personnel. On December 16, 1976, a damaging earthquake of magnitude 5.0 to 5.5 was recorded at Welkom, South Africa. A schematic structure section of the area is shown in Figure 14. The surface damage was extreme, with large structures failing. Displacements ≤10 cm were noted in the mine at a depth of 2.0 km. The focal depth of the earthquake was ∿6 km.

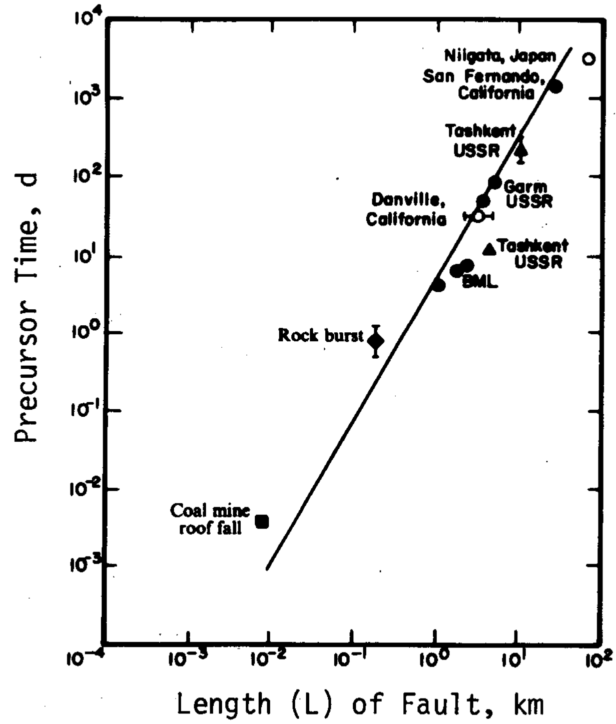

FIGURE 13. Precursor Time for Several Different Failures as a Function of Source Dimension[37]

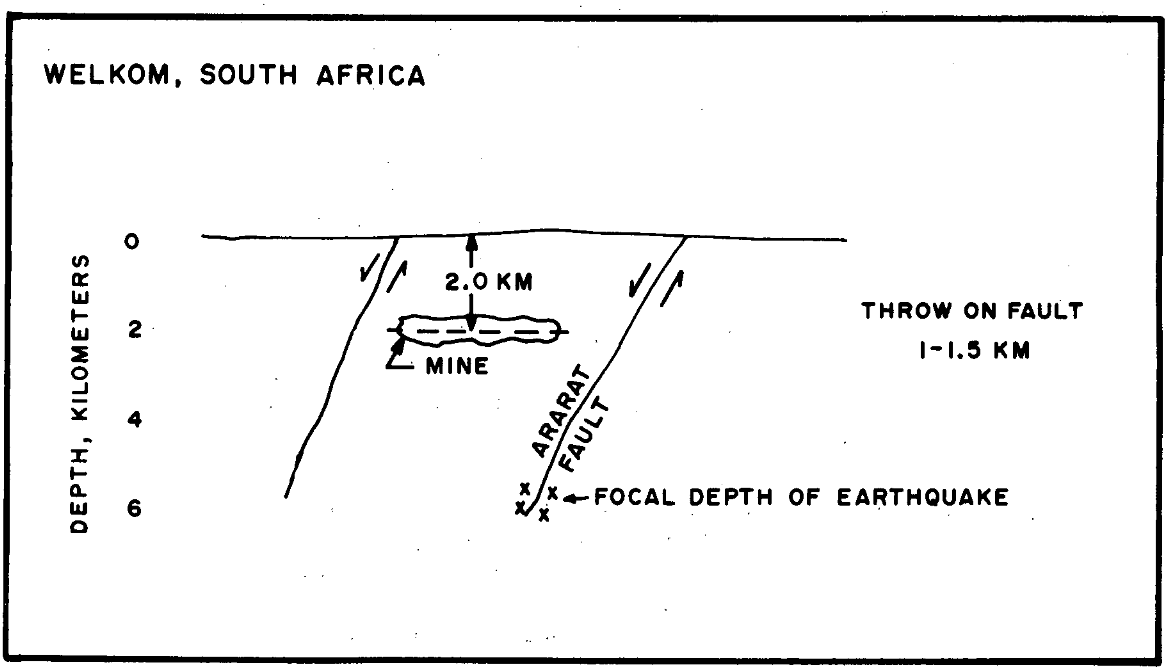

FIGURE 14. Schematic Cross Section of Structural Setting of Earthquake at Welkom, South Africa, December 1976

In both the Rand Gold district and the Orange Free State district, studies were conducted to assess the relationship of acceleration, displacement, and frequency of earthquakes to magnitude during the mining operation. These mines are up to 4 km in depth. McGarr[38] noted that shear displacements on the order of 5 to 10 cm were associated with magnitude of 2 to 3 rock bursts due to resulting stress redistribution. It must be emphasized that these displacements were measured once the area was mined so these displacements represent relative movement in intact rock away from a free surface. These data are very important and may give us, along with the data at Welkom, some indications of upper bounds of displacements near earthquake sources in these very hard rocks.

The U. S. G. S.[39] reported in the lessons and conclusions of the Alaskan earthquake of 1964 that no significant damage was reported to underground facilities, such as mines, and tunnels, as a result of the earthquake, although some rocks were shaken loose in places. Included in this analysis were studies of the coal mines in the Matanuska Valley which were undamaged, the railroad tunnels near Whittier, the tunnel and penstocks at the Eklutna hydroelectric project, and the Chugach Electric Association tunnel between Cooper Lake and Kenai Lake. There were also no reports of damage to the oil and gas wells in and along Cook Inlet.

The reports of non-damage from the Alaskan earthquake are significant. This earthquake was one of the largest (M = 8.5) to occur in this century, and surface damage was extreme.

Stevens[40] summarizes the nature and geography of earthquakes and gives numerous examples pertaining to the effects of earthquakes on underground structures. Because instrumentally derived seismological data have been available for only about 70 years, the principal sources for the reports are eyewitness accounts; these made it exceedingly difficult to quantify the effects of the earthquakes. The following incidents from Stevens concentrate on those events which had significant effects on the surface or in the subsurface, and also on those which have quantitative data associated with them.

An earthquake was reportedly felt 457 m underground at Virginia City, June 6, 1868.[40] Observers state that during an earthquake at Virginia City, the mines were not caved in or damaged; however, in some mines, the flow of water was greatly increased, while at Gold Hill, it was generally diminished.

On August 22, 1952, the strong aftershock of the Kern County earthquake caused concern for a party touring through Crystal Cave. The quake was felt generally in the area of Sequoia

National Park; however, no one in the party underground noticed the earthquake.

During the 1960 Chilean earthquake, one of the strongest earthquakes on record, miners in coal mines heard strange noises but felt no effects of the quake. Later examination of these mines, which extend under the ocean, showed several old faults, but no new movement.[40]

Stevens[40] has several general conclusions:

- Effects on mines are less severe than surface effects.
  - Severe damage is inevitable when a mine or tunnel intersects a fault along which movement occurs during an earthquake.
  - Mines in epicentral region of strong earthquakes, but not transected by fault movement, may suffer severe damage by shaking. Stevens did not define the word severe quantitatively.
  - Mines outside of epicentral regions are likely to suffer little or no damage from a strong earthquake.
- Damage to mines is most insignificant when they are located in highly competent, unweathered rock; greatest damage occurs in mines found in loose unconsolidated or incompetent rock. This is due to the diminished effect of shaking in competent rock; unconsolidated sediment is much more susceptible to damage caused by shaking.

Similar results were reported by Cooke[41] for the Peru earthquake of May 31, 1970. The earthquake of Richter magnitude 7.7 did no damage to 16 railroad tunnels totaling 1740 m under little cover in zones of MM VII to VIII intensity. Also no damage was reported to the underground works of a hydroelectric plant and 3 coal and 2 lead zinc mines in the MM VII intensity zone.

A number of mines are located in areas where earthquakes frequently occur; however, many of these areas are not studied scientifically, and so reports of possible damage do not exist. Japan is particularly significant because it is highly seismic, and records should exist. Europe is less seismic, but it too has been carefully investigated.

A summary of recent (1977) data from foreign sources based on personal communication and literature is presented below.

In Europe, we were unable to find any significant reports of damage to deep underground structures and mines due to earthquakes. We have corresponded with seismologists primarily in Switzerland and Germany, but records of damage do not exist.[42]

Professor K. Mogi of the Earthquake Research Institute reported that he knew of no damage in mines in Japan.[43] However, Professor K. Aki at Massachusetts Institute of Technology noted that a railroad tunnel on the main Tokyo line was offset during the 1930 Kita Izu earthquake nearby.[44] Professor Y. Nishimatsu[30] of the Engineering Faculty at the University of Tokyo reported that there were no records of damage from coal mines near the epicenter of the Tokachi Oki earthquakes of 1952 and 1968. One mine operator reported a small rock burst soon after the 1968 shock, suggesting a possible triggering by the earthquake. The records kept in the coal mines are complete, and the negative report above suggests that, in general, damage due to earthquakes is negligible.

Nishimatsu[30] has made a finite element study of strain in underground openings. He reported strains of nearly 10^{-6} for an acceleration of 50 gal (gal - a unit of acceleration equivalent to one centimeter per second per second).

The Japanese, as reported by Iwasaki et al.[45] obtained acceleration records to depths of 150 m below the surface during a five-year period from bore-hole accelerometers installed at four locations around Tokyo Bay. Three of the sites were in sands and clays; however, the site at Kannonzaki was in a siltstone. During the period of operation, data were obtained from 16 earthquakes ranging in magnitude from 4.8 to 7.2. The results are presented in Table 2,[45] which gives the accelerations recorded at the four sites and the important earthquake parameters.

Iwasaki et al.[45] concluded from the analysis of the accelerations recorded in the bore holes at the different depths that:

- The distribution of the maximum accelerations, with respect to depths, changes considerably with the change of soil conditions near the ground surface. Ratios of the surface acceleration to that at the deeper layer (110 to 150 m) are about 1.5 at a rocky ground, 1.5 to 3 at sandy grounds, and 2.5 to 3.5 at a very clayey ground.

TABLE 2

Maximum Accelerations (gal) During 16 Moderate Earthquakes Recorded Around Tokyo Bay, 1970-1975[45]

EQ No.	Date Magnitude Epicenter	Component	Futtsu Cape 0 m	Futtsu Cape -70m	Futtsu Cape -110m	Ukishima Park 0 m	Ukishima Park -27m	Ukishima Park -67m	Ukishima Park -127m	Kannonzaki 0 m	Kannonzaki -80m	Kannonzaki -120m	Ohgishima 0 m	Ohgishima -15m	Ohgishima -38m	Ohgishima -150m	Remarks
1	9.30.1970	NS	28.2	16.0	7.8	11.8	10.7	5.5	4.3								H=40 km
	M=4.8	EW	29.4	9.8	11.2	17.8	11.2	6.0	3.4								Δ≒10~30 km
	Eastern Kanagawa-ken	UD	8.4	4.2	6.4	7.8	3.8	1.8	2.0								Mouth of Tama River
2	7.23.1971	NS	5.6	2.5	2.7	16.8	13.3	5.6	6.4	12.4	5.3	4.9					H=40 km
	M=5.3	EW	8.6	2.6	4.3	12.3	11.8	5.0	3.5	6.7	5.5	8.5					Δ≒60~80 km
	Eastern Yamanashi-ken	UD	2.2	1.2	1.3	5.7	3.3	3.0	2.6	5.4	4.1	3.4					
3	2.29.1972	NS	46.1	32.3	18.6					10.3	13.1	12.2					H=70 km
	M=7.2	EW	51.6	23.6	21.6					8.6	14.9	14.6					Δ≒300 km
	E OFF Hachijo	UD	17.2	10.9	13.3					6.0	11.3	10.4					
4	10.18.1972	NS	6.4	3.5	2.1	6.5	5.8	3.7	3.1	6.1	4.6	3.1					H=80 km
	M=5.1	EW	8.0	3.3	2.5	12.0	9.6	2.1	3.6	17.2	3.0	3.5					Δ≒50~70 km
	Northern Chiba-ken	UD	2.8	1.3	1.2	4.2	2.8	1.6	1.1	4.0	2.1	1.8					
5	11. 6.1972	NS	2.8	1.6	0.8	3.3	3.2	2.0	1.8								H=40 km
	M=5.1	EW	3.2	1.4	1.4	8.1	6.3	2.5	1.6								Δ≒60~90 km
	SW Ibaraki-ken	UD	1.8	0.9	0.9	2.2	1.4	0.9	0.9								
6	12. 4.1972	NS				20.0	14.6	7.4	6.4	6.5	10.1	10.4					H=50 km
	M=7.2	EW				15.6	11.3	7.1	4.7	7.3	10.6	10.7					Δ≒300~320 km
	E Off Hachijo	UD				4.1	3.6	3.0	3.0	—	—	—					
7	12. 8.1972	NS	12.3	7.2	3.2	10.1	9.3	5.3	4.4	8.3	5.0	4.2					H=90 km
	M=4.8	EW	7.0	3.6	8.5	13.4	10.4	4.2	3.3	16.8	5.9	5.3					Δ≒20~40 km
	Northern Tokyo Bay	UD	4.0	1.8	2.1	3.7	2.4	1.6	1.5	6.1	2.5	2.5					
8	3.27.1973	NS	47.5	30.7	7.4					18.6	25.9	16.8					H=60 km
	M=4.9	EW	42.1	12.3	13.7					31.5	26.7	—					Δ≒20~40 km
	Tokyo Bay	UD	7.1	6.5	5.8					8.5	9.3	5.4					
9	12.22.1973	NS	10.5	8.5	2.6					13.0	6.4	6.0					H=70 km
	M=5.0	EW	7.6	4.3	7.8					18.4	7.3	7.4					Δ≒50~55 km
	Southern Chiba-ken	UD	3.4	1.8	2.3					6.3	3.0	3.9					
10	5. 9.1974	NS	38.0	22.3	28.7					30.0	14.7	11.5					H=10 km
	M=6.9	EW	40.6	26.4	13.7					37.7	17.7	22.4					Δ≒110~120 km
	S Coast of Izu Pen.	UD	13.9	6.8	7.1					12.5	6.9	5.5					Off Izu Pen. Eq.
11	7. 8.1974	NS	4.1	2.4	0.9	4.2	2.0	2.9	1.0	3.5	1.9	1.5					H=40 km
	M=6.3	EW	3.3	1.9	2.0	3.3	0.7	1.3	1.7	3.6	1.9	2.0					Δ≒160~190 km
	Off Ibaraki-ken	UD	2.3	1.7	1.3	1.5	1.0	1.0	1.0	2.0	1.9	1.2					
12	8. 4.1974	NS				13.6	10.6	6.5	5.1	12.5	6.5	4.9	12.1	7.1	8.5	6.2	H=50 km
	M=5.8	EW				12.9	7.7	5.5	4.4	15.0	7.1	6.5	8.2	6.0	10.8	4.8	Δ≒60~90 km
	SW Ibaraki-ken	UD				5.8	3.1	2.0	1.9	4.5	4.5	3.2	10.7	4.7	—	3.4	
13	9.27.1974	NS	11.8	7.0	5.0	7.0	5.9	3.7	3.1				4.7	5.0	5.0	2.9	H=40 km
	M=6.5	EW	10.2	7.1	5.9	5.5	5.0	3.3	1.9				5.9	3.9	5.5	3.2	Δ≒240 km
	SE Off Boso pen	UD	6.9	4.0	3.0	3.1	2.0	1.3	1.3				4.5	2.5	2.3	1.6	
14	11.16.1974	NS				4.8	4.0	3.0	2.8				5.4	3.4	2.9	1.8	H=40 km
	M=6.1	EW				4.8	2.6	2.2	1.7				3.6	4.2	3.3	1.9	Δ≒140 km
	Near Choshi Chiba-ken	UD				1.7	1.2	1.6	1.2				3.1	2.8	2.9	1.4	
15	11.30.1974	NS	11.6	8.5	4.0	6.2	7.0	2.5	2.8				6.2	3.2	5.6	4.2	H=350 km
	M=7.5~7.75	EW	8.5	5.8	4.5	5.3	5.0	2.9	2.2				6.2	3.4	6.8	3.6	Δ≒550 km
	Near Tori-shima	UD	4.7	3.1	2.8	2.3	1.7	1.3	1.1				3.7	2.2	2.4	1.5	
16	2. 8.1975	NS				14.2	9.3	4.8	4.2								H=50 km
	M=5.4	EW				18.9	16.6	7.5	5.5								Δ≒50 km
	Northern Chiba-ken	UD				5.6	3.1	2.6	2.0								

- Although the acceleration values are smaller at deeper layers, frequency characteristics of underground seismic motions are close to those of the surface motions.
- The characteristics of earthquake ground motions appear to be influenced by seismic conditions, such as magnitudes of earthquakes, epicentral distances, etc., as well as soil conditions at the site.

The damage to underground tunnels and mines does not have a large data base, especially with respect to measured displacement. However, the relation between velocity (and thus distance for M = 5, 6, and 6.5) and damage level has been summarized by Rozen.[2] Strong tensile and some radial cracking was noted at surface velocities of 152 cm/sec which would occur at distances of about 7-8 km during a magnitude 6.5 earthquake. Even at these levels seismic damage would be negligible in competent rock (Figure 15).[2]

The data for measured displacements as a function of depth are summarized in Figure 16. Surface displacements range from at least 1 to 10 m, depending on geology, magnitude, etc., but decrease markedly with depth. Displacements of ≤25 cm have been measured at 100-m depth in *in situ* rock masses. Displacements of <7 m have been noted along pre-existing faults. The data base below 500 m is almost negligible. The one data point from South Africa needs more detailed study of displacement, rock type, and local tectonic environment.

Wells

The damage to water and oil wells has been documented in a limited number of reports. Failure of water wells is primarily due to sanding or silting; however, in some instances, there has been crushing, bending, or shearing of the casing due to differential movement of the surrounding rock. The latter mode of failure has also affected some oil wells. The damage to wells appears to be more of a near-surface phenomenon than one at depths of >100 m, except where the well crosses a fault.

The damage to wells during the earthquake on July 21, 1952 in Kern County, California has been summarized by Steinbrugge and Moran.[8] Surveys were made of the oil and gas fields in the area by the oil companies almost immediately after the earthquake; however, detailed surveys were not made until 10 days after the earthquake when noticeable changes began to occur in the operations of the fields. Variations in production were pronounced in the Tejon Ranch, Kern River, and Frustvale fields which trend approximately north-south from about Bakersfield to Wheeler Ridge, California. The greatest amount of damage to subsurface equipment occurred in the Tejon Ranch field where several shallow

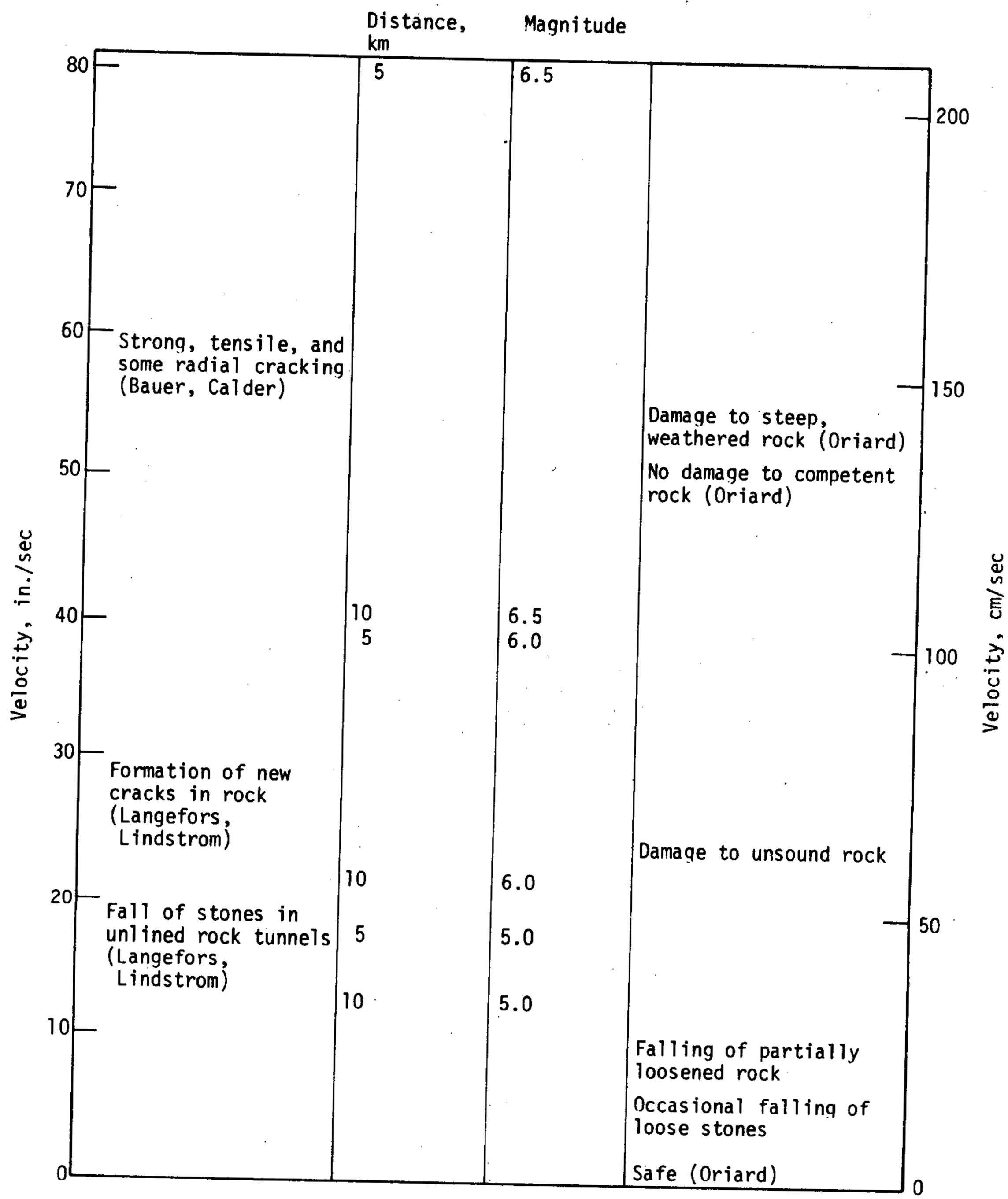

FIGURE 15. Summary of Damage Levels[2]

wells were found to have the casing collapsed or tubing kinked. In 6 wells, it was necessary to redrill the well. In the Kern River field, 150 wells were found to be sanded up as a result of the earthquake, but no cases of damage to the casings were found. The investigations revealed that the greatest effects of the earthquake were predominantly in the fields producing from soft unconsolidated formations.

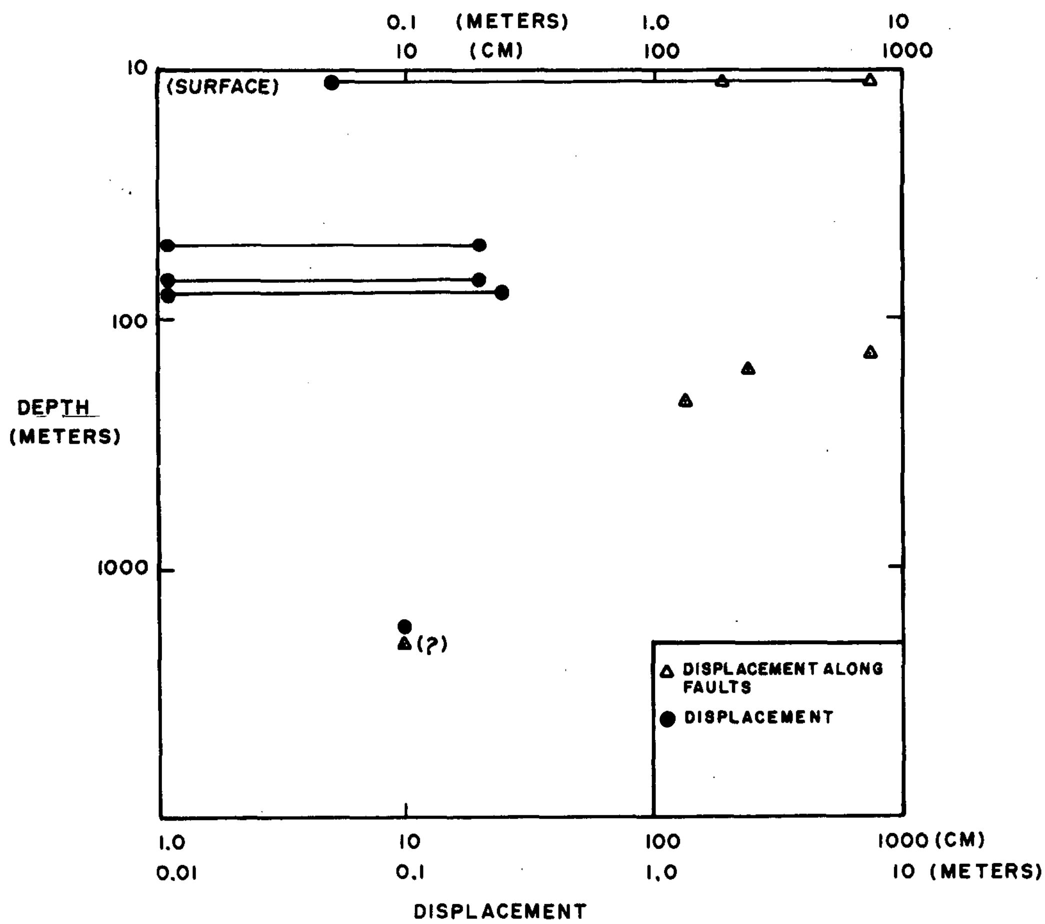

FIGURE 16. Measured Range of Displacements as a Function of Depth

The U. S. G. S. documented the effects of the Alaska earthquake, March 27, 1964, on wells throughout most of Alaska and the changes in water levels noted in the lower 48. Waller[46,47] summarized the damage to wells in Alaska as mainly due to sanding or silting of the well or differential movement of casing caused by movement of the surrounding rock. Table 3 lists those wells reported by Waller as damaged and pertinent details on each. A detailed tabulation of data, mainly from the Anchorage areas, summarized from Waller is presented in Appendix B. Three city wells were damaged in Anchorage and possibly one private well. The three city wells were all damaged by movement resulting in bent or broken casing. One of the damaged wells was in artificial fill where differential movement bent the casing; however, the casing was straightened and the well was put back into service. The other two city wells were in or near the Turnagain slide area and were destroyed by the lateral movement. Three city wells in Seward were damaged and rendered useless by ground movement and fissuring; in Valdez, one well had the casing sheared at a threaded joint 4.7 m below ground surface. Near Yakataga, one abandoned exploratory oil well was sheared off. No damage was reported to any of the oil and gas wells in and along Cook Inlet.

After the earthquake (M = 5.5) in Southern Illinois on November 9, 1968, the Illinois State Geological Survey made a survey in the area; the results were reported by Heigold.[48] One old plugged gas well suffered cracks in the casing apparently as a result of the earthquake, and a few well structures in the immediate vicinity of the epicenter were damaged.

Some damage to wells occurred during the earthquake on February 9, 1971, in San Fernando, California.[49,50] Minor damage was reported to a few oil wells in the area, and all seven wells which supplied water to the city of San Fernando suffered damage during the earthquake causing a severe water supply problem.

Oil wells in the greater Los Angeles area which cross faults have had the casing ruptured by movement along the faults; however, it is uncertain if the movement is creep of a tectonic origin or settlement due to subsidence.

Damage to wells in the San Joaquin Valley due to compaction of sediments caused by the withdrawal of ground water is relatively common, but this damage is due to aseimic causes.

A reduction in peak acceleration of a factor of 5, from 0.05 g at the surface to 0.01g at the depth of 165 m in a borehole, was noted during the Briones[38] earthquake (M_L = 4.5).[51] The borehole was located in the Hayward fault in Berkeley, California.

TABLE 3

Wells Damaged by Alaska Earthquake of March 1964[46]

Location[a]	*Depth, m*	*Diameter, m*	*Earthquake Effects*
Anchorage	143.2	0.2032	Casing bent and broken. East of the downtown section near Mountain View. Generally in clay with a few lenses of sand and gravel.
Anchorage	23.5	0.1524	Casing damaged (?). Private well, extent of damage unknown, new well drilled. On southern edge of town. In gravelly clay.
Anchorage	151.5	0.2032	Casing severely damaged, well destroyed by movement (slide) of soil. In the Turnagain Heights area. In clay with several thick sand layers and a few gravelly sands.
Anchorage	31.1	0.1524	Casing destroyed, probably by movement of the surrounding material. Near the Turnagain Heights area. In clay with some gravelly clay and sand near bottom.
Valdez	7.3	—	Casing bent seaward by land movement and sheared at threaded joint 4.7 m below ground surface. In outwash plane of glacier.
Seward	30.5	—	Damaged; casing bent by movement of rock.
Seward	30.5	—	Damaged by movement of a portion of the alluvial fan; casing bent.
Seward	30.5	—	Survived quake; about one month later pump turbine jammed because of slow ground movement or settlement.

a. In a survey of 106 wells in Anchorage, Valdez, and Seward, these were the only wells damaged, although others commonly showed some effect such as a change in water level or the water becoming muddy for a period.

In general, the performance of wells during earthquakes is quite good, with the major damage resulting from bending, crushing, or shearing of the casing due to differential movement of the surrounding rock. In general, the major damage appears to be to shallow wells that are in unconsolidated sediments and near the surface. There is very little damage to wells deeper than about 100 m except where the well cross a fault plane along which movement occurs.

Nuclear Events as Earthquake Simulators

The use of nuclear events as equivalent earthquake sources has been discussed by a number of people.[11,52,53] The data from nuclear events can be useful in assessing the potential damage from earthquakes to underground facilities. The resulting velocities, accelerations, and displacements from nuclear events have been monitored carefully because of their importance to defense-related issues. In many cases, the data are obtained at conditions that would be near the hypocenter of the earthquake and thus more severe than would be anticipated from any earthquake affecting a nuclear waste repository. It should be possible, however, to place certain bounds on the maximum accelerations, velocities, and displacements expected from comparable earthquakes. This would be helpful in establishing damage criteria for potential earthquake damage to waste repositories. It is again emphasized that this report is not meant to arrive at any damage criteria for a repository, but to gather the available data and begin to assess damage criteria that might ultimately be used for the seismic risk assessment of nuclear waste repositories.

At the outset, it is important to compare nuclear events with earthquakes to determine the scaling relationships between the two. An important point to make is that a comparable magnitude only indicates that P-wave signals from both earthquakes and explosions are of equal strength. However, nuclear explosions tend to produce much weaker surface waves than do earthquakes of comparable body-wave magnitude (Figure 17). As a consequence, the surface wave energy associated with an earthquake of a given body-wave magnitude is on the order of ten times that of an explosion of an equal body-wave magnitude.[11] Therefore, a magnitude 5 explosion does not have the same potential for causing ground motion damage at the surface, as does a magnitude 5 earthquake. Table 4 lists several nuclear events of interest. Figure 18[11] gives the body-wave magnitude as a function of yield for explosions in various rock types. Events of interest are in salt (GNOME, SALMON), granite (PILEDRIVER, HARDHAT, and SHOAL), andesite (LONGSHOT, CANNIKIN, MILROW), and basalt (DANNYBOY).

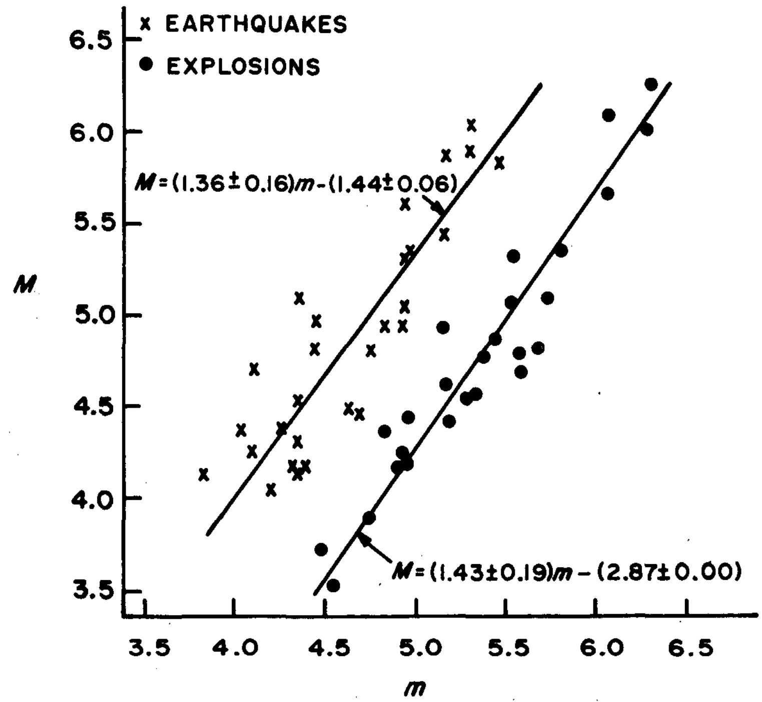

FIGURE 17. Mean Surface-Wave Magnitude (M) Versus Body-Wave Magnitude (m) for 28 Earthquakes and 26 Nuclear Explosions in Southwestern North America, as determined by Canadian Measurements[11]

TABLE 4

Data from Nuclear Events

Event	*Region*	*Medium*	*Nominal Yield, kt*	*Magnitude*
PILEDRIVER	NTS Area 15	Granite	61	5.6
HARDHAT	NTS Area 15	Granite	5.9	4.2
SHOAL	Fallon, NV	Granite	13	4.7
GREELEY	NTS Pahute Mesa	Tuff	1030	6.0
HALF BEAK	NTS Pahute Mesa	Rhyolite	365	6.0
BOXCAR	NTS Pahute Mesa	Rhyolite	1200	6.3
SEDAN	NTS Yucca Flat	Alluvium	100	4.2
LONGSHOT	Amchitak, AK	Andesite	81	5.9
MILROW	Amchitak, AK	Andesite	1200	6.1
CANNIKIN	Amchitak, AK	Andesite	5000	6.8-7.0
RULISON	Grand Valley, CO	SS.8 Shale	40	
SALMON	Hattiesburg, MI	Salt	5.0	
GNOME	Carlsbad, NM	Salt	3.1	

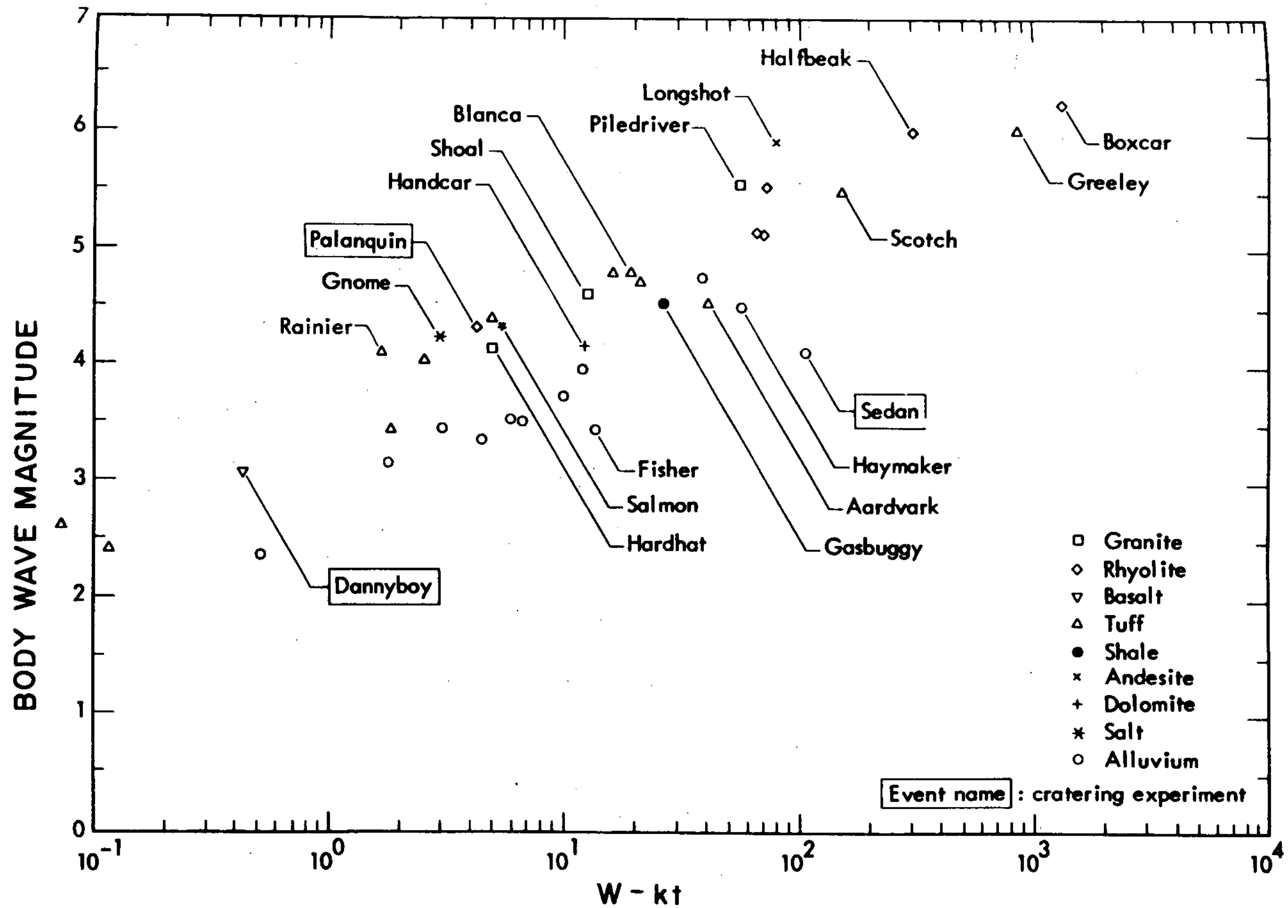

FIGURE 18. Body-Wave Magnitude Versus Explosion Yield and Rock Type[11]

It will therefore be necessary to compare explosions and earthquakes based on criteria such as accelerations and displacements. One method of doing this is to plot the pseudo-relative velocity (PSRV) curves for various magnitude explosions and relate them to the PSRV curves from earthquakes at equivalent distances. PSRV curves for nuclear events are shown in Figure 19 for the range of 1 to 1000 kilotons (kt).[11] R. Simonson (Terra Tek) compared the response spectrum for a megaton (Mt) shot at a scaled depth of ~1991 m with the 1940 El Centro earthquake (M = 7.1) response spectrum (Figure 20). The results from the earthquake are similar to the BOXCAR event acceleration curve for 0.33 g maximum acceleration up to one-second period. Beyond one second, the acceleration is lower for the explosion. The BOXCAR acceleration curve is data taken 12.6 km from ground zero.

Figure 21 shows the PSRV response of the north-south component from the 1940 El Centro earthquake and the north-south component from Las Vegas for the BOXCAR event.[54] The spectral plot is used to estimate damage prediction, and the threshold evaluation scale to analyze buildings and the effects of building damage from ground motion. The BOXCAR event had a body-wave magnitude of ~6.5. The BOXCAR event showed much lower acceleration, velocity, and displacement than did the El Centro north-south. The spectral response in terms of velocities, accelerations, and displacements is also shown for the BOXCAR event (Figure 22).[54]

Direct measurement from large explosions in the Alaskan peninsula volcanic rock (andesite) yields significant data for near-field measurements of accelerations, velocity, and displacement.[9] Measurements at the surface are important in assessing the role of pre-existing discontinuities in the resulting permanent displacements along faults in the neighborhood of explosions. These can be compared with the acceleration, velocity, and displacement measurements downhole. The problem of course, with the downhole measurements is that they are in the near-field region in an area of extremely high accelerations, far greater than those that would be expected in the repository unless the earthquake was directly at the repository. These however, will be important upper bounds for the trends of resulting accelerations and displacements that might occur.

The three events of interest are LONGSHOT, MILROW, and CANNIKIN whose event statistics are given in Table 5.[9] Peak values of acceleration, peak velocity, and displacement from both subsurface and surface stations are shown in Tables 6 and 7. Of particular interest are the vertical scaled acceleration, velocity, and displacement observed at MILROW and CANNIKIN. Even though subsurface motion data are also in the very high acceleration range, the peak and residual displacement values associated with these near-field distances from the event are of interest.

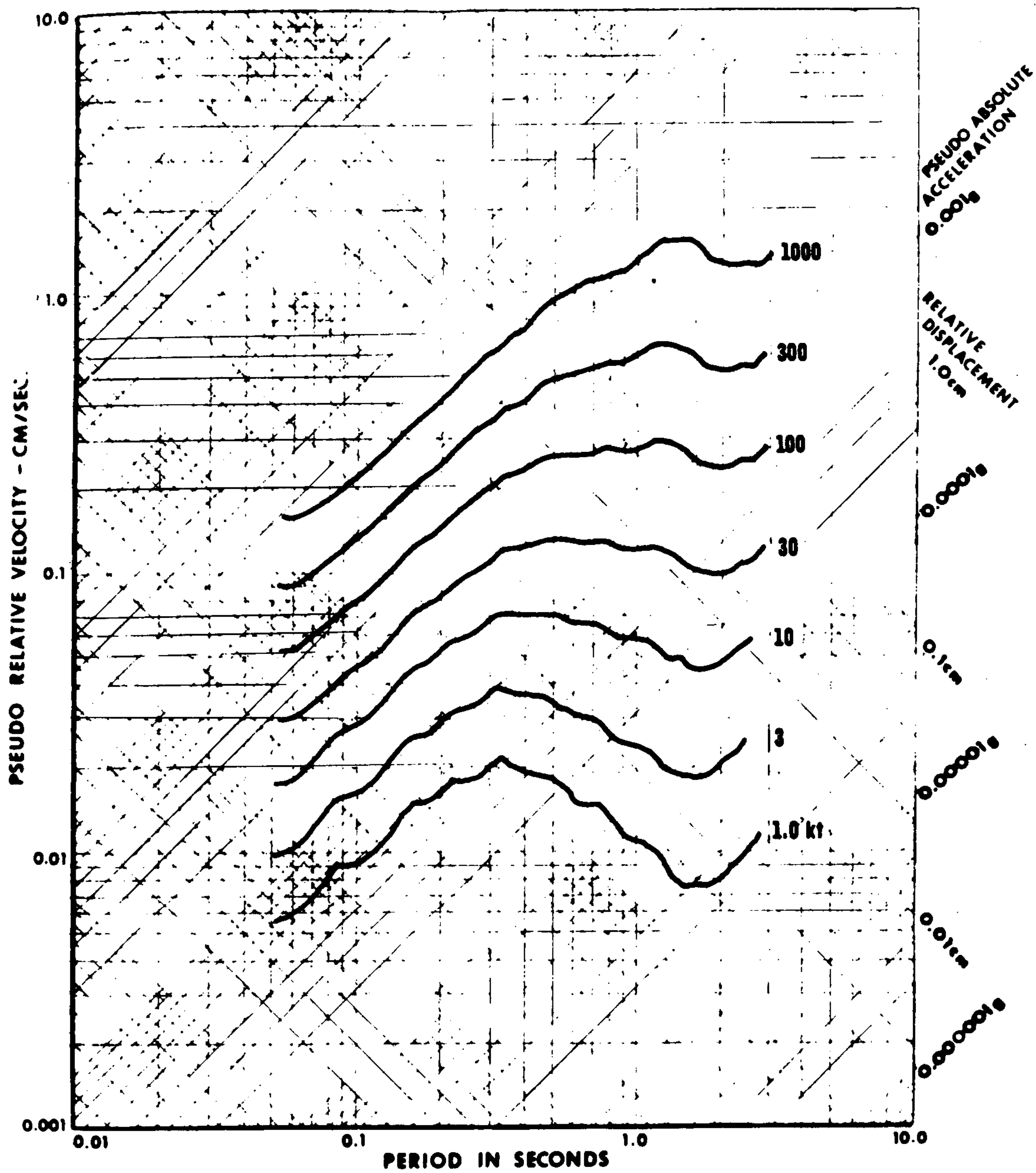

FIGURE 19. A Family of Predicted Mean Pseudo-Relative Response Velocity Curves for Seven Yields with 5% Damping at a Distance of 100 km[11]

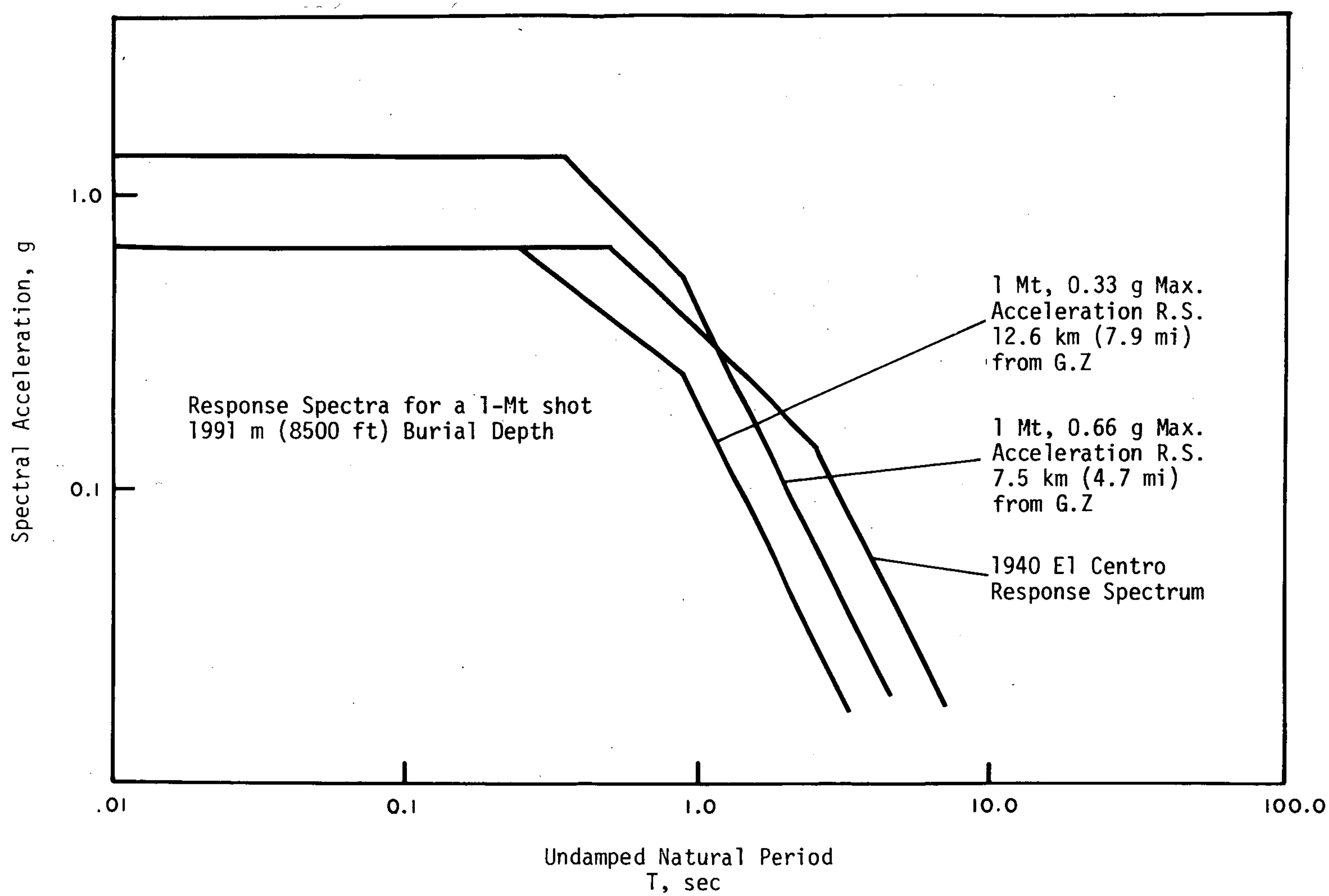

FIGURE 20. Acceleration as a Function of Period for the 1940 El Centro Earthquake and a Buried 1-Mt Nuclear Event[58]

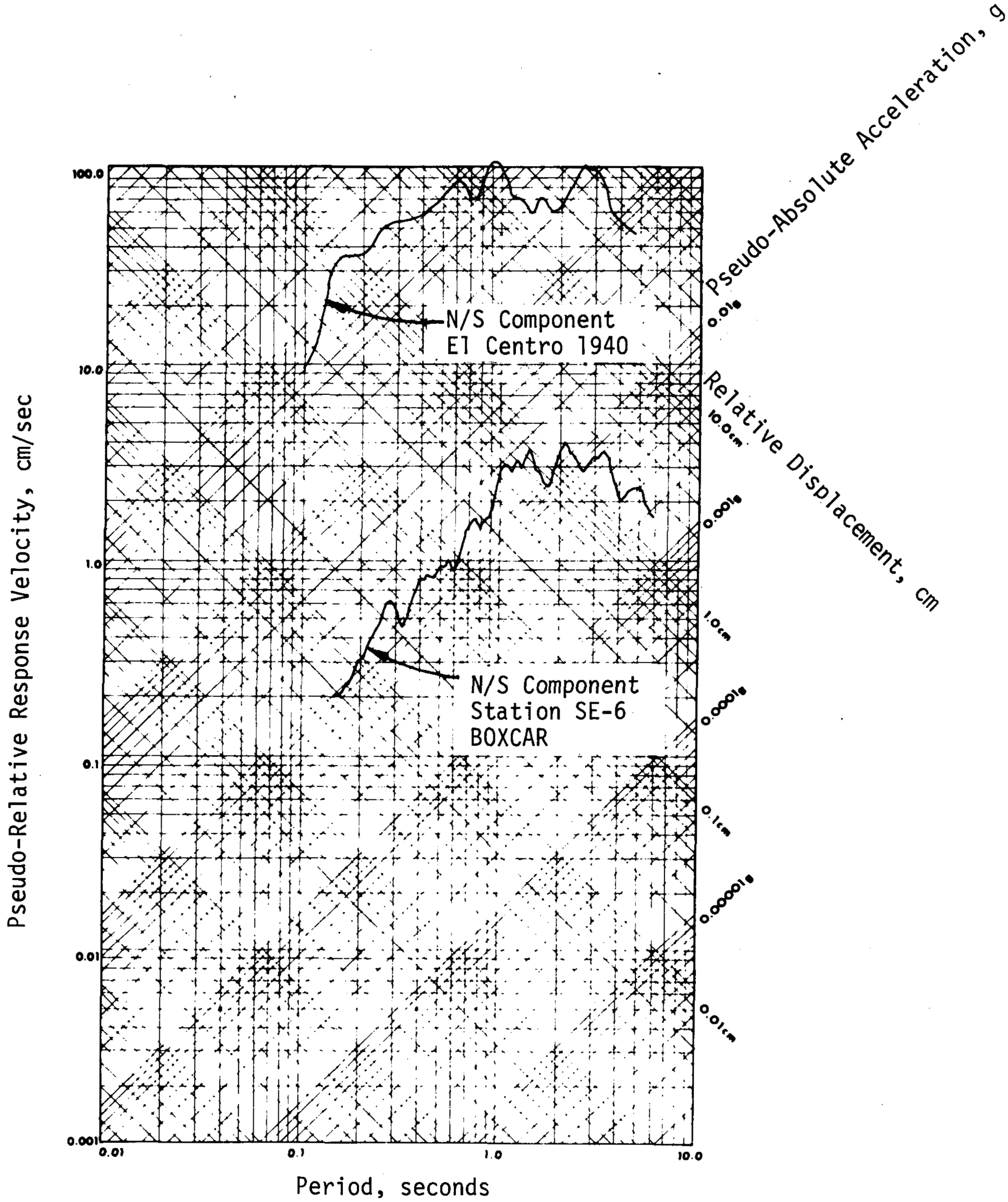

FIGURE 21. Pseudo-Relative Response Velocity Versus Damped Spectral Response[54]

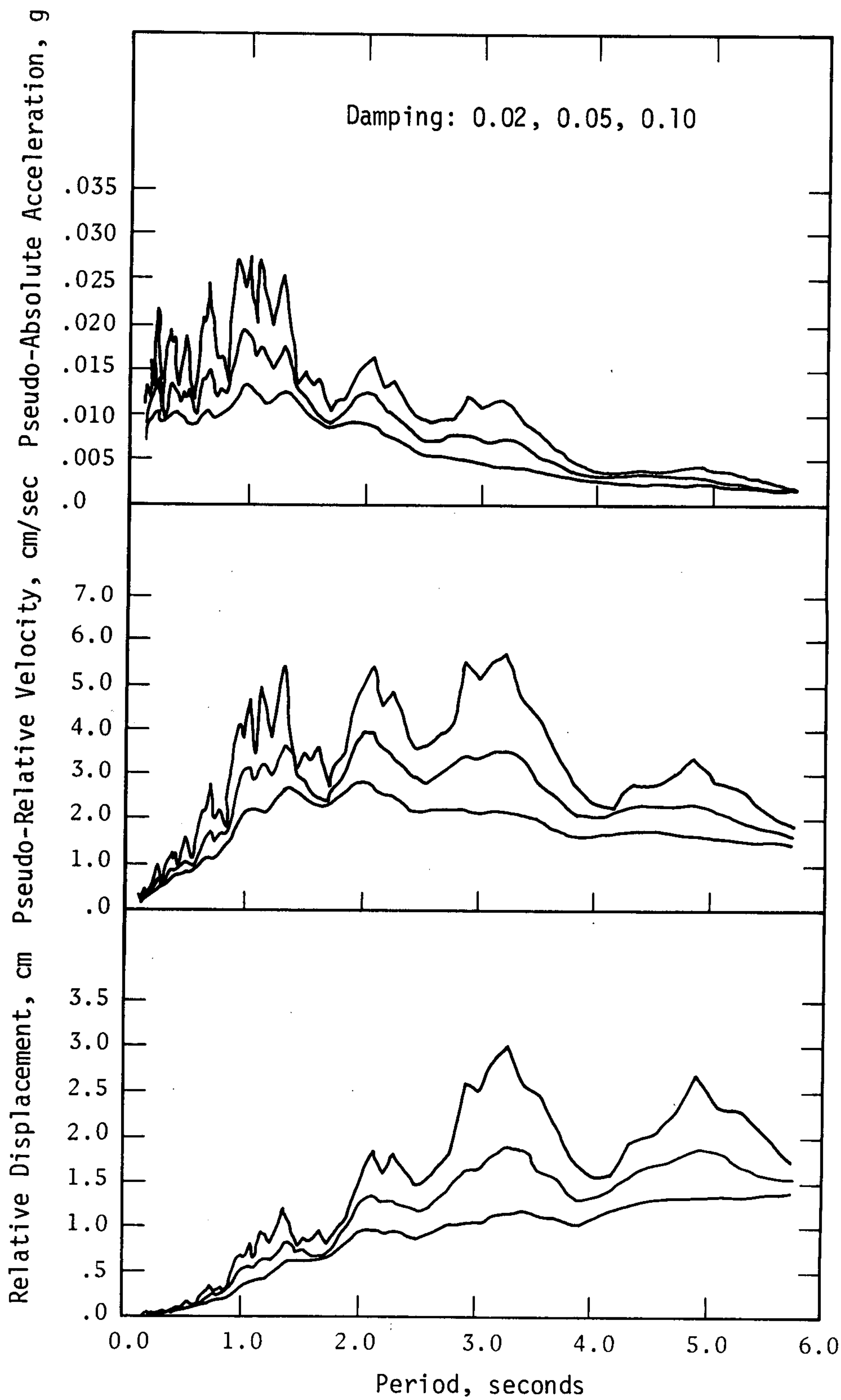

FIGURE 22. Spectral Response to Ground Motion at Station SE-G, N/S Component, Las Vegas, Event BOXCAR (L-7)[54]

TABLE 5

Nuclear Event Statistics for LONGSHOT, MILROW, and CANNIKIN[9]

Event	*LONGSHOT*	*MILROW*	*CANNIKIN*
Date	10/29/65	10/2/69	11/6/71
Depth, meters	701	1219	1791
Rock	Volcanic Breccia	Pillow Lava	Pillow Lava
Yield, kilotons	81	~1000	<5000

TABLE 6

MILROW and CANNIKIN Subsurface Motion Data[9]

					Particle Velocity		*Displacement*	
Station No.	*Depth, m*	*Slant Range, m*	*Arrival Time, sec*	*Acceleration, g*	*Peak, m/sec*	*Pos. Phase, sec*	*Peak, m*	*Residual, m*
MILROW								
I-1-20	609.6	616.3	0.1465	67.3	11.3	>0.073	>6	-
I-1-25	457.2	767.5	0.1372	36.1	8.35	1.38	3.53	+2.6
I-1-30	304.8	919.0	0.2332	27.3	9.57	2.05	4.65	+4.7
I-1-33	132.4	1071	0.2772	24.5	5.03	1.32	2.59	+1.7
I-2-37	91.4	1131	0.2983	19.6	6.71	1.04	3.68	+1.4
I-2-39	30.5	1192	0.3152	20.7	8.90	1.03	4.93	+1.7
CANNIKIN								
I-25	1042	753.8	0.155	110	18.6	>0.20	>2	-
I-30	888	906.5	0.198	57	18.3	>0.17	>2	-
I-40	623	1171	0.260	30	14.6	>0.45	>2.5	-
I-45	470	1324	0.305	14	6.1	>0.57	>1.2	-
I-50	316	1477	0.348	12	5.8	>0.52	>1.3	-
I-55	162	1630	0.400	12	6.7	>0.46	>2.1	-
I-57	90.8	1702	0.425	16	7.6	>0.20	>1.2	-
I-58	60.0	1732	0.435	18	11.0	0.57	>2.8	-
I-59	30.8	1762	0.450	19	10.0	1.26	5.69	-

TABLE 7

MILROW Surface Motion Data[9]

Station No.	Component	Range, m Horizontal	Range, m Slant	Arrival Time, sec	Acceleration, g[a] Initial	Acceleration, g[a] Impact	Particle Velocity,[a] Positive, m/sec	Particle Velocity,[a] Pos. Phase, sec	Negative, m/sec	Displacement,[a] sec
S-0	Vert.	75.6	1220	0.328	35.5	10.3	8.44	1.1	-6.83	4.32
	Rad.			-	1.6	2.9	0.49	1.9	-0.70	0.61
	Tang.			-	-	-	0.22	-	-0.23	0.03
S-2	Vert.	572.7	1350	0.368	14.1	10.4	4.79	0.64	-3.20	1.50
	Rad.			-	2.5	-7.8	0.91	1.1	-1.07	0.64
	Tang.			-	1.2	6.6	0.37	-	-1.10	0.05
S-4	Vert.	1225	1733	0.471	6.9	28.2	3.29	0.47	-3.23	0.79
	Rad.			-	2.1	10.1	0.67	1.1	-0.73	0.53
	Tang.			-	-	-	0.14	-	-0.37	-0.07
S-5	Vert.	1354	1792	0.482	5.8	8.4	4.24	0.36	-3.75	0.81
SF-6	Vert.	1837	2196	0.620	8.6	19.4	1.86	0.30	-2.38	0.30
	Tang.			-	-0.9	-3.9	0.34	0.70	-0.34	-0.13
SF-7	Vert.	2010	2350	0.628	2.7	20.5	1.22	0.26	-2.26	0.18
	Tang.			-	0.82	-3.1	0.46	0.53	-0.28	-0.08
S-8	Vert.	2405	2697	0.722	3.2	6.2	1.83	0.24	-1.80	0.23
	Rad.			-	1.5	4.3	0.76	1.1	-0.37	0.28
	Tang.			-	-	-	0.46	-	-0.49	-0.11
S-11	Vert.	3491	3696	1.000	-	-	0.98	0.27	-1.04	0.15
	Rad.			-	-	-	0.43	-	-0.55	0.22
S-17	Vert.	5199	5339	1.405	1.6	1.8	0.76	0.21	-0.79	0.08
	Rad.			-	0.73	-	0.43	0.34	-0.26	0.08
	Tang.			-	-	-	0.12	-	-0.10	0.04
S-32	Vert.	9852	9930	2.401	0.25	0.16	0.21	0.22	-0.25	0.02
	Rad.				0.19	0.30	0.14	0.34	-0.18	0.02
	Tang.				0.03	0.10	0.05	-	-0.05	0.01

a. Positive motion is upward in vertical components, outward in radial components, and clockwise in tangential components.

At distances of ∿1 km, between 2.5 and 5 m of peak displacement was noted, but only 1.7 m or less of final residual displacement. These data are for accelerations on the order of 20 g's. CANNIKIN must be remembered as a very large 5000 kiloton nuclear weapon equivalent to an earthquake of a body-wave magnitude of ∿7. MILROW was a smaller event with peak displacements of less than 2 meters at a kilometer range. The residual displacements were not measured. The scaled surface vertical displacement attenuation of the Alaskan event is shown in Figure 23.[9] The vertical displacement scales as

$$\delta_V/W^{1/3} = 1.26 \times 10^6 (R/W^{1/3})^{-2.28 \pm 0.19}$$

where

δ_V = vertical displacement, cm

R = range, m

W = charge weight, kt

Motion along faults that were mapped prior to the MILROW event in Alaska indicates that a maximum of 30 cm of vertical displacement and 10 cm of strike slip displacement resulted from the event (Figure 24).[9] The distance of the Rifle Range fault was 1.9 km from the MILROW surface ground zero and gives a good indication of what displacements are like at those ranges. Two faults northwest of the CANNIKIN site were bracketed at those ranges. Two stations were on the opposite side of Teal Creek fault 1.5 km from surface ground zero and indicated a surface fault motion of 0.3 m in the case of the Teal Creek fault strike slip displacement and a vertical displacement on the order of 1.0 m. The differential motion across another fault at a distance of 3.0 km was 0.25 m strike slip displacement and the order of 0.2 m of vertical displacement. At these distances, accelerations are ~50 g's, equivalent to being near the epicenter of a major earthquake. However, it is difficult to relate these data to the subsurface data.

Cooper[54] summarized the velocity and stress data for nuclear events in hard rock and indicates that velocity generally falls off as

$$U_V = 1.6 \times 10^4 (R/W^{1/3})^{-1.6}$$

for scaled radius (Figure 25).[55] The Alaskan events are included in the data base. The data from softer rock (tuff) fall below the scatter band for hard rock.

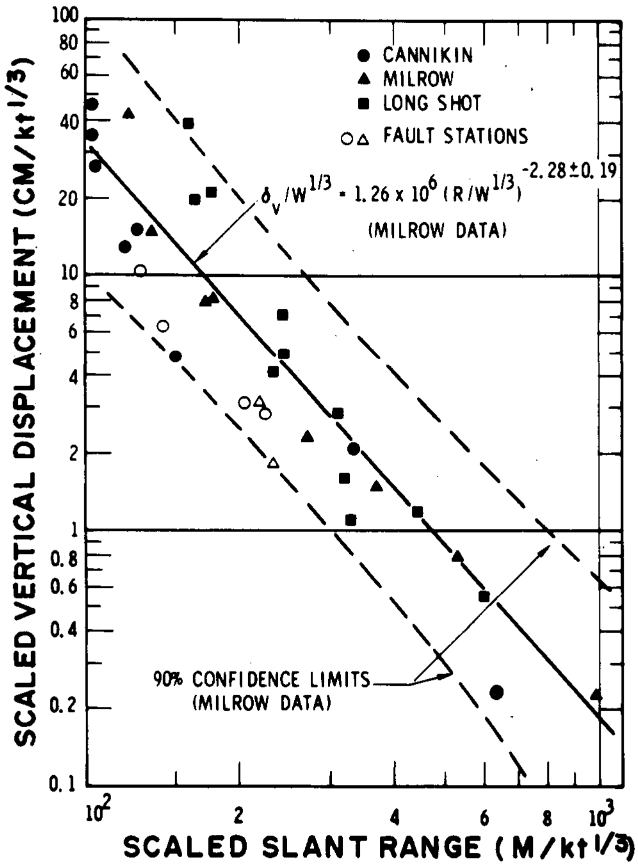

FIGURE 23. Surface Vertical Displacement Attenuation[9]

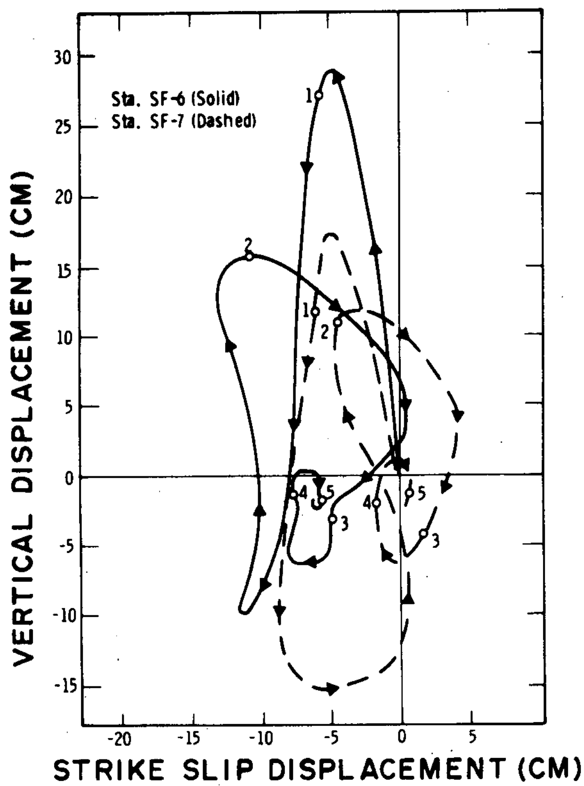

FIGURE 24. MILROW Fault Displacement Hodographs, Rifle Range Fault[9]

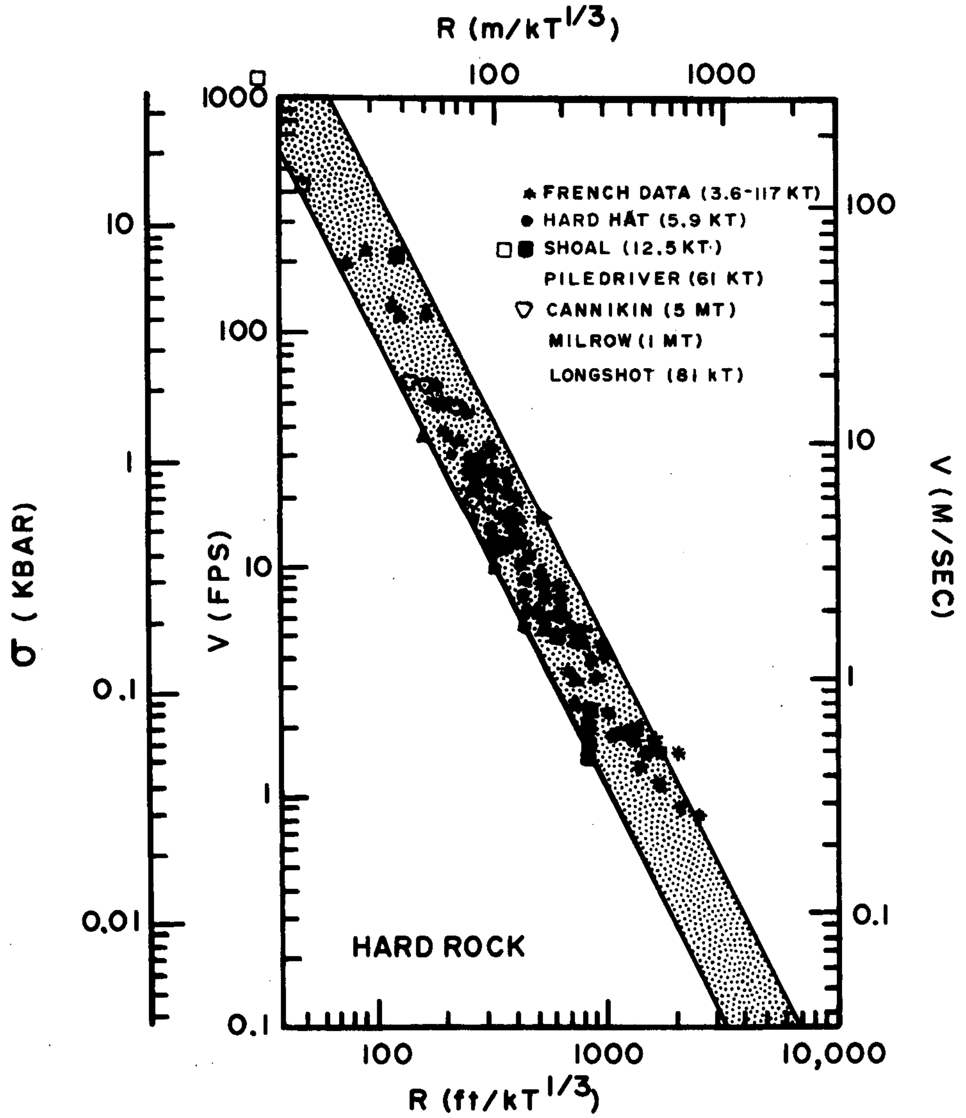

FIGURE 25. Velocity and Stress as a Function of Scaled Range[55]

Important observational data exist from the PILEDRIVER event in granite at the Nevada Test Site (NTS). The senior author, Pratt, visited the site and noted that there was no apparent permanent displacement at a range of 425 m where accelerations were measured at approximately 30 g's. The rock was jointed but not faulted in the area observed. The conclusion is that there was no large-scale differential displacement in this granite rock mass at this acceleration level.

The GNOME nuclear event is of interest because it was located in salt in New Mexico, near the current site of a waste isolation demonstration program. The acceleration data from the 3-kt explosion are shown in Figure 26.[56] These data, obtained in one of the potash mines, fell within a standard deviation of the particle acceleration – distance data obtained from a series of small chemical explosions in the same mine. The regression curve for this acceleration – distance data was

$$AW^{1/3} = 5.10 \times 10^5 (R/W^{1/3})^{-2.43}$$

Thus, this curve can be used with some confidence for predicting scaled accelerations in salt.

Direct observations of vibration response and evaluation of mines observed during nuclear events have been documented for project RIO BLANCO, RULISON, and MIGHTY EPIC.[57-60] RIO BLANCO was a 90-kt event where particle velocity, acceleration, and displacement were recorded at oil shale mines located at slant range distances of 20, 45, and 110 km.[57] Because of the large distances from ground zero to even the nearest mine, the peak velocity recorded was 1.14×10^{-2} cm/sec, peak acceleration of 27.02 cm/sec^2, and maximum displacement of 2.77×10^{-2} cm in the Colony Mine. The seismic waves were relatively short and did not cause any significant visible damage. However, the micro-effects such as opening up subsurface joints and permanent micro-displacement were not analyzed. There was no significant damage due to the RIO BLANCO explosion in the mine. The average spectral response for the roof and floor from the Colony Mine is shown in Figure 27.[57]

The surface motions from project RULISON, a nominal 40-kt device, located in West Central Colorado, for the purpose of natural gas stimulation in sandstone have been studied in detail. The observed peak particle velocity and displacement were measured,[58] and the resulting PSRV plot for station 4 at 9 km is presented in Figure 28.

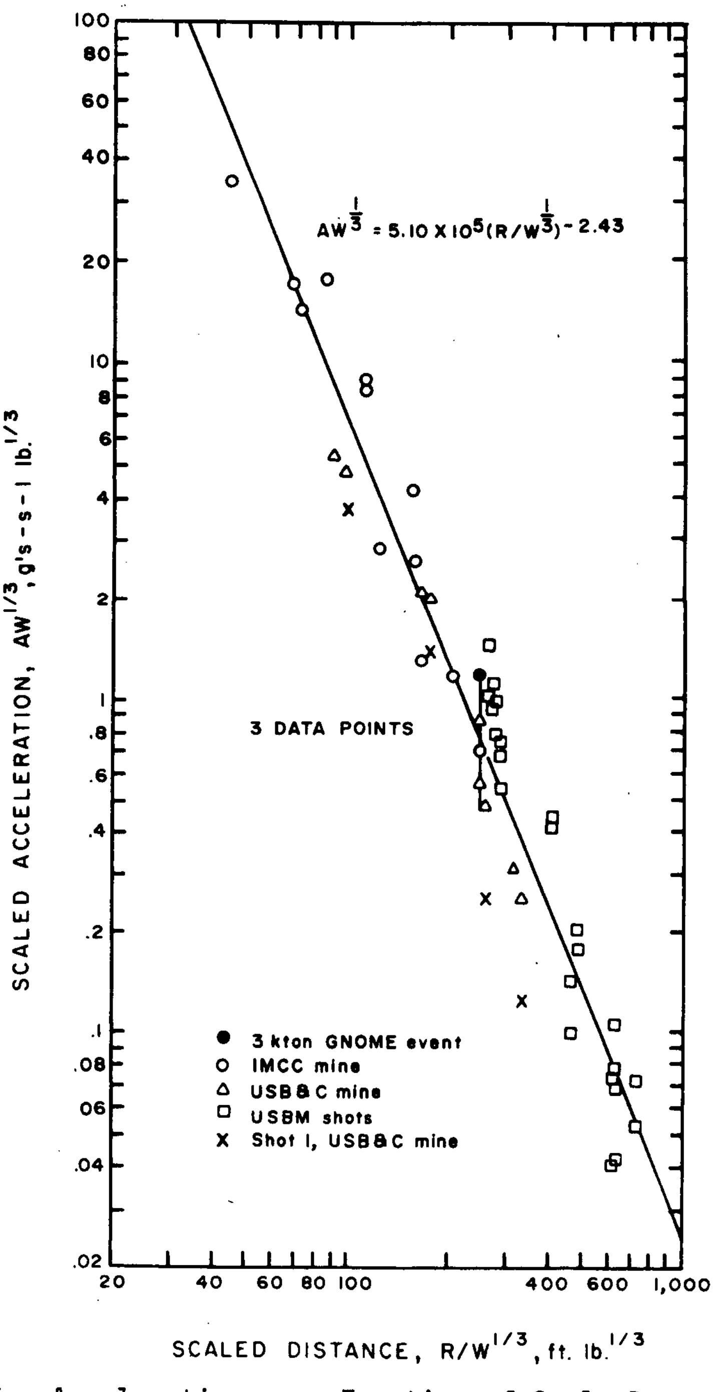

FIGURE 26. Acceleration as a Function of Scale Range for the GNOME Event[56]

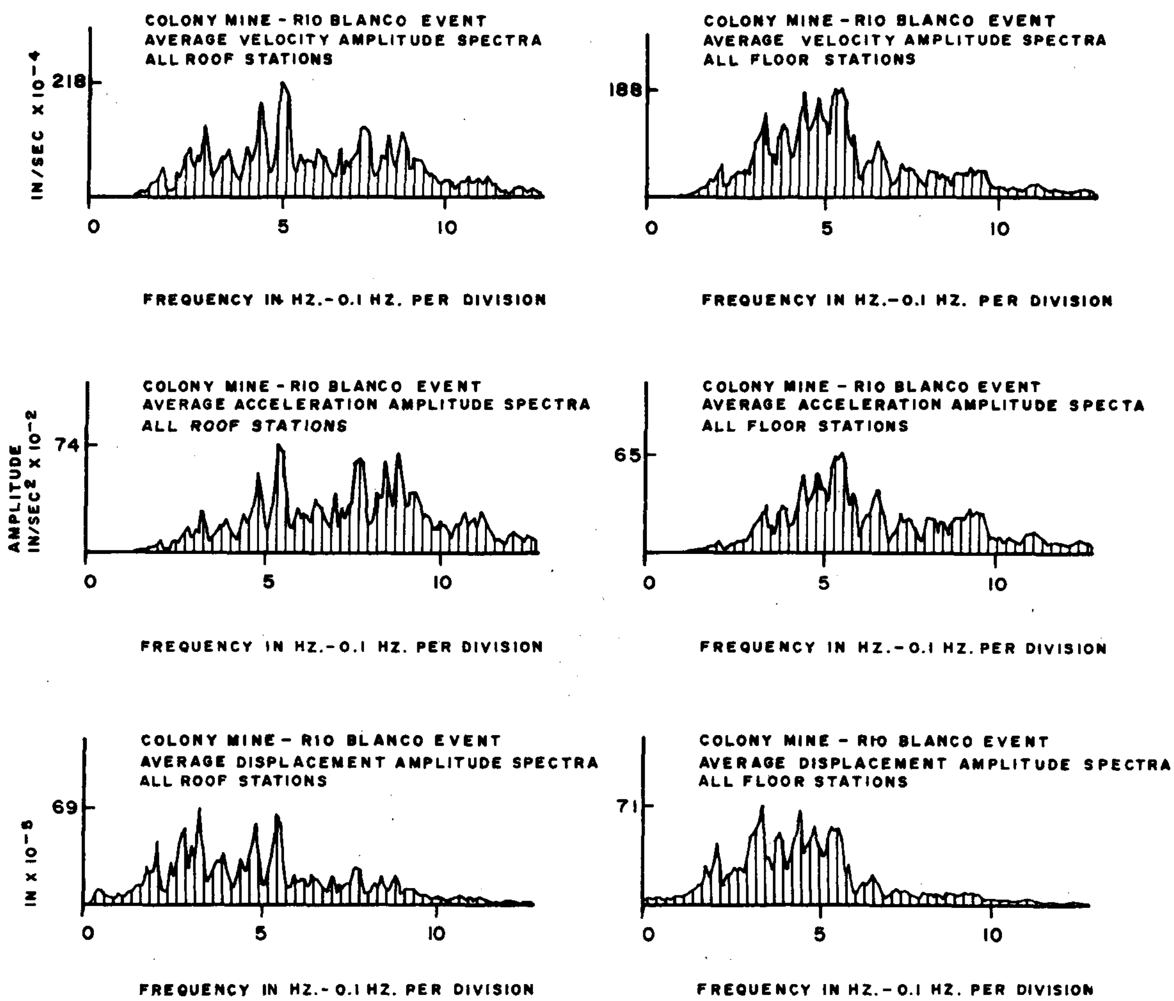

FIGURE 27. Average Spectral Response for the Roof and Floor from the Colony Mine[57]

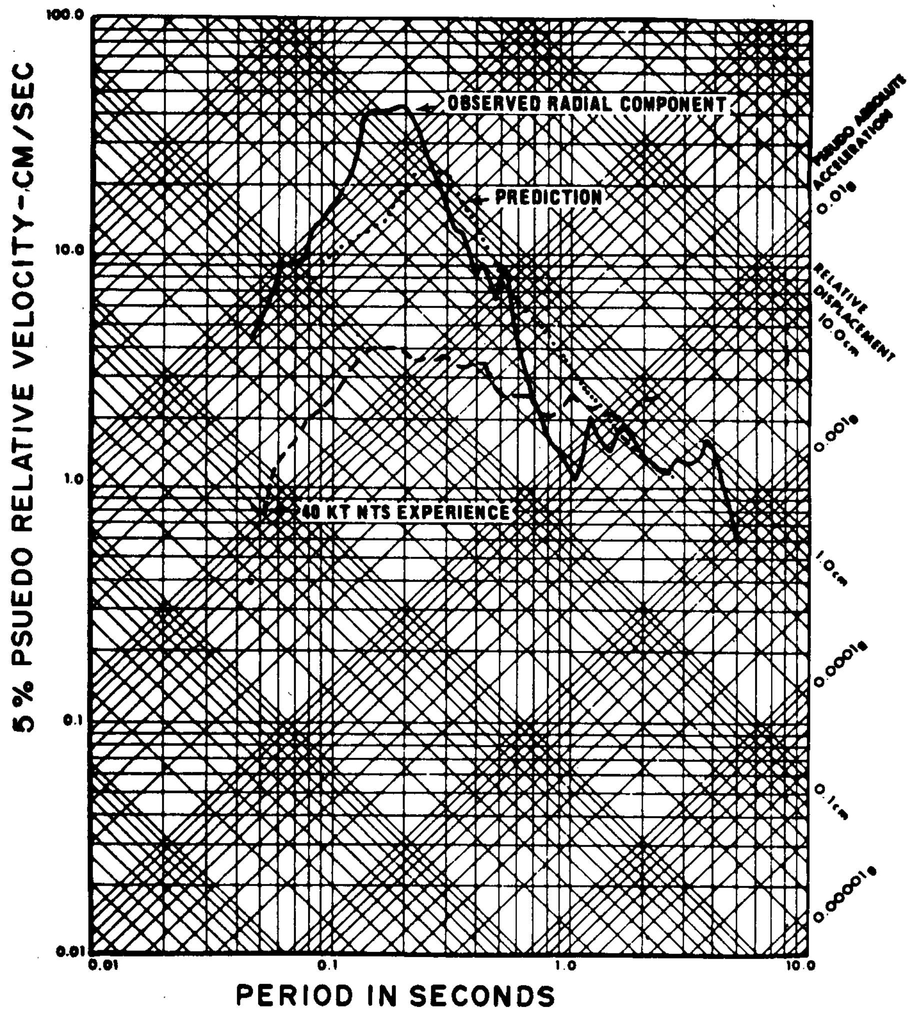

FIGURE 28. Velocity and Stress as a Function of Scaled Range for the RULISON IV Event[58]

The comparison with the 40-kt NTS data is also given in the response spectrum plot. Accelerations of 1.0 g were seen at slant distances of 10 km, and relative displacements about 2.1 cm were noted at distances of 9 km. A body-wave magnitude of 4.5-5.0 was recorded for the RULISON event. Surface damage was noted at a nominal distance of 8 km. Subsurface damage to one well was noted at 3-km radial distance from ground zero.[59] The ground motion from this event was noted in coal mines at distances up to 90 km.[60] There was no resulting damage to the mines at these large distances.

In addition to these events, relative displacement was observed in the MIGHTY EPIC Event at the Nevada Test Site.[61] A displacement of ∿33 cm was noted along a pre-existing discontinuity. This was not one of the major distontinuities in the area, but had been delineated by U.S. Geological Survey mapping in the area. This data point indicates that within a tunnel system, relative block motion can occur at moderate stress levels along a pre-existing discontinuity. The stress level was high enough so that unless a repository was in the immediate vicinity of a large earthquake, displacement of this kind would not likely be observed.

The seismological and geological evidence for block motion displacement associated with underground explosions has also been discussed by Backe and Lambert,[53] based on observations on surface faulting, free field ground motions, and studies of aftershock activity. They conclude that there is a general lack of data in this field, but that the key parameter of block motion is the level of tectonic stress in the region of the explosions. They also concluded that it is unlikely that shearing block motion or large relative displacements occur outside the explosions shatter zone. They conclude from the large 1-Mt BENHAM event that an upper limit on the associated block motions for this event is ∿50 cm at ranges up to 2 km or so. BENHAM was equivalent to a body-wave magnitude 6.5-7.0 earthquake. They also indicate that the data base for surface events is very small, and they focused on data from contained explosion events.

In summary, a large amount of acceleration, velocity, and displacement data in the subsurface are available from nuclear tests. These data are not directly applicable in evaluating subsurface effects of earthquakes at the present time. Evaluation of these data may set upper bounds to the parameters of interest, but earthquakes differ from nuclear tests in several important respects. The surface effects of earthquakes should be greater than that of nuclear tests of equivalent body-wave magnitude because more energy goes into surface waves. Thus earthquakes of equivalent body-wave magnitude are of higher total energy content. Also a nuclear test is a point source of energy; but an earthquake is usually a dispersed source.

Until there is a quantitative correlation of earthquakes with nuclear tests, this wealth of data should only be used qualitatively.

CONCLUSIONS

The potential seismic risk for an underground nuclear waste repository will be one of the considerations in evaluating the possible locations. A literature search and evaluation were performed to document the damage or non-damage to underground facilities due to earthquakes. Damage was delineated in terms of displacements and accelerations. The sources of data include both U.S. and foreign experiences of earthquake damage to tunnels, mines, wells, and other underground facilities. An analysis of the damage from documented nuclear events was also evaluted where applicable.

The major conclusions developed from an assessment of the information obtained in this study are summarized as follows:

- There are very few data on damage in the subsurface due to earthquakes. This fact itself attests to the lessened effect of earthquakes in the subsurface because mines exist in areas where strong earthquakes have done extensive surface damage.
- More damage is reported in shallow, near-surface tunnels than in deep mines. Specifically, data are very sparse below 500 m.
- In mines and tunnels, large displacements occur primarily along pre-existing faults and fractures or at the surface entrance to these facilities.
- Data indicate vertical structures such as wells and shaft are also not as susceptible to damage as are surface facilities. Even in the Alaska earthquake of 1964 (M = 8.5) few wells were damaged in Anchorage except those sheared by landslides.
- Not enough data were found to assess the exact influence of rock type; however, the effects are less in consolidated materials than unconsolidated materials, such as alluvium. Geologic structures, such as faults, seem to be a dominant factor in underground damage.
- Frequencies most likely to cause damage to subsurface facilities are significantly higher (50-100 Hz) than the frequencies (2-10 Hz) that cause damage to surface facilities.
- Acceleration and displacement data from nuclear explosions can give close-in upperbound limits for large earthquakes when a facility is very near the epicenter.
- More analysis is required before a seismic criteria can be formulated for the siting of a nuclear waste repository.

APPENDIX A - EARTHQUAKE DAMAGE TO TUNNELS

(Data Summarized from Reference 2)

			Damage Due to		
No.	*Earthquake*	*Tunnel*	*Shaking*	*Fault Movement*	*Ground Failure and Other Reasons*
1	Central CA (San Francisco)	Wright-1	Caving in of rock and some breaking of timber but to lesser extent compared to damage near the fault.	Caving in of rock from roof and sides. Breaking in flexure of upright timber. Upward heaving of rails. Breaking of ties. Blocked in several points. Transverse horizontal offset of 4.5 ft under the fault.	
1a		Wright-1	No damage.		
1b		Wright-1	No damage.		
2	San Francisco, 1906	Wright-2	Broken timber, roof caved in.		
2a		Wright-2	No damage.		
2b		Wright-2	No damage.		
3	Tokyo, 1923 (Kwanto)	Terao			Cracked brick portal.
4		Hichigama			Landslide at entrance.
5		Taura			Landslide at entrance.
6		Numama			Cracked brick portal.
7		Nokogiri-Yama	Concrete walls fractured slightly. Some spalling of concrete.		
8		Kanome-Yama			Entrance buried by landslide. Some damage to masonry portal.
9		Ajo			Landslides at entrance. Damage to masonry portal.
10		Ippamatzu	Masonry dislodged near floor in interior.		Cracks in masonry near portals.
11		Nagoye	Interior cracked.		
12		Komine	Destroyed. RC blocks tilted. Ceiling slabs caved in. Formed section cracked.		

No.	Earthquake	Tunnel	Damage Due to: Shaking	Fault Movement	Ground Failure and Other Reasons
13		Fudu San	Clean interior.		Cracked masonry portal.
14		Meno-Kamiama	Partial collapse.		
15		Yonegami-Yama	Minor interior masonry damage.		Cracks near portal.
16		Shimomaki-Matsu	Deformed masonry in interior.		Portals closed by slides.
17		Happon-Matsu	Badly cracked interior.		Buried by slides.
18		Nagasahu Yama	Some interior fractures in brick and concrete.		
19		Hakone-1	Interior cracked.		
20		Hakone-2	Undamaged.		
21		Hakone-3	Cracks in interior.		Ceiling collapsed near portal. Some damage to masonry portal.
22		Hakone-4	Collapse of loose material.		Entrance almost completely buried.
23		Hakone-7	Interior collapse.		Landslides buried entrances.
24		Yose	Shallow portions collapsed and daylighted.		
25		Doki	Collapses at shallow parts.		
26		Humuya	Cave in. Cracks with 10-inch (25 cm) displacement.		Landslide.
27		Mineoka-Yama	Cracks in bulges in masonry from local earth pressure.		
28	Idu Peninsula, 1930	Tanna	Few cracks in walls.	7 ft 10 in. horizontal displacement, 2-ft vertical displacement just across the Tanna fault.	
29	Fukui, 1948	Kumasaka			Brick arches of portal partially fractured.
30	Off Tokachi, 1952		Minor cracks in both brick and concrete linings.		

No.	Earthquake	Tunnel	Damage Due to: Shaking	Fault Movement	Ground Failure and Other Reasons
31	Kern County, 1952	S. P. R. R. 3		Wrecked under White Wolf fault. Daylighted.	
31a	(Aftershock)	S. P. R. R. 3	No damage.		
31b	(Aftershock)	S. P. R. R. 3	No damage.		
32		S. P. R. R. 4		Wrecked under fault. Daylighted.	
33		S. P. R. R. 5		Wrecked under fault.	
33a	(Aftershock)	S. P. R. R. 5	No damage.		
33b	(Aftershock)	S. P. R. R. 5	No damage.		
34		S. P. R. R. 6		Fractured, daylighted.	
34a	(Aftershock)	S. P. R. R. 6	No damage.		
34b	(Aftershock)	S. P. R. R. 6	No damage.		
35	Kita Mino, 1961	Powerhouse	No damage.		
36		Aqueduct	Cracking.		
37	Niigata, 1964	Nezugaseki	Spalling of concrete at crown.		Cracking at portal.
38		Terasaka	Spalling of concrete at crown, crushing of invert at bottom of sidewalls.		
39	Great Alaska 1964	Whittier-1	Some overhead ravelling of loose rock which falls on the track.		
40		Whittier-2	No damage.		
41		Seward-1	No damage.		
42		Seward-2	No damage.		
43		Seward-3	No damage.		
44		Seward-4	No damage.		
45		Seward-5	No damage.		
46		Seward-6	No damage.		
47	San Fernando, 1971	Balboa		Severe spalling, breaking of concrete lining, deformations where tunnel passed under canyon at shallow cover, only 36 m (120 ft) south of Santa Suzana fault. No breaking of reinforcing bar at RC blocks.	

No.	Earthquake	Tunnel	Damage Due to Shaking	Fault Movement	Ground Failure and Other Reasons
48		San Fernando		Maximum displacement and damage near Sylmar fault.	A large vertical displacement of 2.3 m along 9 km, causing flexural cracks.
49		McLay	Wide long cracks. No local buckling.		
50		Chatsworth	Slight damage.		
51		Tehachapi-1	No damage.		
52		Van Norman Inlet	No damage.		
53		Tehachapi-2	No damage.		
54		Tehachapi-3	No damage.		
55		Carley Porter	No damage.		
56		Van Norman North	Hundreds of new fractures in concrete lining. No structural damage. Fractures primarily circumferential, also longitudinal and diagonal.		
57		Saugus	No damage.		
58		San Francisquito			
59		Elizabeth	No damage.		
60		Antelope	No damage.		
61	Inyokern, 1946	Jabbine-1	No damage.		
62		Jabbine-2	No damage.		
63		Jabbine-3	No damage.		
64		Freeman	No damage.		
65	Arvin, Tehachapi	Saugus	No damage.		
66		San Francisquito	No damage.		
67		Elizabeth	No damage.		
68		Antelope	No damage.		
69		Jawbone	No damage.		
70	Chalome, 1927	Jawbone	No damage.		
71		Freeman	No damage.		

EARTHQUAKES' DATA

No.	*Earthquake*	*Tunnel*	*M*	*R*	*Depth*	*a*	*v*	*d*	I_o	*Duration*
1	San Francisco, 1906	Wright-1	8.16	135	15	0.13	26.9	42.1	10 RF	40
1a			6.1	40	15	0.10	10.4	10.4		<10
1b			6.6	20	15	0.23	25.7	23.7		~10
2	San Francisco	Wright-2	8.3	135.8	15	0.13	26.8	41.9	10 RF	40
2a			6.1	42.7	15	0.10	9.9	10.0		<10
2b			6.6	25	15	0.20	22.7	21.6		~10
3	Kwanto, 1923	Terao	8.16	31.6	10	0.47	82.5	91.8		35
4		Hichigama	8.16	36.4	10	0.42	74.8	99.1		35
5		Taura	8.16	31.6	10	0.47	82.5	91.8		35
6		Numama	8.16	46.0	10	0.35	62.8	75.1		35
7		Nokogiri-Yama	8.16	70.7	10	0.24	43.9	57.7		35
8		Kanome-Yama	8.16	26.9	10	0.52	91.6	117.1		35
9		Ajo	8.16	25.0	10	0.55	95.8	112.5		35
10		Ippamatzu	8.16	25.0	10	0.55	95.8	112.5		35
11		Naguye	8.16	24.0	10	0.50	98.1	107.4		35
12		Komine	8.16	26.9	10	0.52	91.6	99.1		35
13		Fudu San	8.16	24.0	10	0.50	98.1	107.4		35
14		Meno Kamiana	8.16	32.0	10	0.46	81.8	91.2		35
15		Yonegami-Yama	8.16	32.0	10	0.46	81.8	91.2		35
16		Shimomaki	8.16	36.5	10	0.42	74.7	85.3		35
17		Happon Matsu	8.16	20.0	10	0.63	108.7	112.5		35
18		Nagashu Yama	8.16	22.4	10	0.59	102.1	107.4		35
19	Kwanto, 1923	Hakone-1	8.16	15.6	10	0.72	123.0	123.2		35
20		Hakone-2	8.16	15.6	10	0.72	123.0	123.2		35
21		Hakone-3	8.16	17.2	10	0.69	117.4	119.0		35
22		Hakone-4	8.16	19.7	10	0.64	109.6	113.1		35

M = magnitude
R = distance from the earthquake, km
Depth = depth to hypocenter, km
a = acceleration, cm/sec
v = velocity, cm/sec
d = displacement, cm
I_o = intensity at epicenter
Duration = seconds

No.	Earthquake	Tunnel	M	R	Depth	a	v	d	I_o	Duration
23		Hakone-7	8.16	22.4	10	0.59	102.1	107.4		35
24		Yose	8.16	26.9	10	0.52	91.6	99.1		35
25		Doki	8.16	61.0	10	0.27	49.9	63.4		35
26		Hamuya	8.16	63.0	10	0.26	48.5	62.1		35
27		Mineoka Yama	8.16	65.0	10	0.26	47.3	60.9		35
28	Idu, 1930	Tanna	7.0	0	-					15
29	Fukui, 1948	Kumasaka	7.2	25.0	10	0.30	39.5	39.3		15-20
30	Off Tokachi, 1952	-	8.0	?	?				4-5	30-35
31	Kern County, 1952	S. P. R. R. 3	7.6	46.0	20	0.24	37.5	42.9		10-15
31a	-	S. P. R. R. 3	6.1	29.0	20	0.13	13.0	12.2		<10
31b	-	S. P. R. R. 3	5.8	21.0	20	0.14	12.0	10.4		~5
32	Kern County, 1952	S. P. R. R. 4	7.6	46.0	20	0.35	37.5	42.9		10-15
33		S. P. R. R. 5	7.6	46.5	20	0.24	37.2	42.7		10-15
33a	-	S. P. R. R. 5	6.1	16.0	15	0.19	18.1	15.6		<10
33b	-	S. P. R. R. 5	5.8	16.0	15	0.16	13.8	11.5		~5
34	Kern County, 1952	S. P. R. R. 6	7.6	46.5	20	0.24	37.2	42.7		10-15
34a	-	S. P. R. R. 6	6.1	16.0	15	0.19	18.1	15.6		<10
34b	-	S. P. R. R. 6	5.8	16.0	15	0.16	13.8	11.5		~5
35	Kita Mino, 1961	Powerhouse	7.2	32.0	25	0.25	33.7	39.3		15-20
36		Aqueduct	7.2	?	25					15-20
37	Niigata, 1964	Nezugaseki	7.5	?	40					20-25
38		Terasaka	7.5	?	40					20-25
39	Alaska, 1964	Whittier-1	8.4	75.0	30	0.26	52.0	79.4		45
40		Whittier-2	8.4	75.0	30	0.26	52.0	79.4		45
41		Seward-1	8.4	85.0	30	0.23	46.3	64.8		45
42		Seward-2	8.4	85.0	30	0.23	46.3	64.8		45
43		Seward-3	8.4	100	30	0.19	39.7	60.9		45

No.	*Earthquake*	*Tunnel*	*M*	*R*	*Depth*	*a*	*v*	*d*	I_o	*Duration*
44		Seward-4	8.4	100	30	0.19	39.7	60.9		45
45		Seward-5	8.4	110	30	0.19	36.2	56.7		45
46		Seward-6	8.4	115	30	0.17	34.7	56.7		45
47	San Fernando, 1971	Balboa	6.4	16	13	0.23	23.9	21.0	8-9	15
48	San Fernando, 1971	San Fernando	6.4	16	13	0.23	23.9	21.0		15
49	San Fernando, 1971	McLay	6.4	16	13	0.23	23.9	21.0		15
50	San Fernando, 1971	Chatsworth	6.4	20	13	0.20	21.4	19.4		15
51	San Fernando, 1971	Tehachapi-1	6.4	70	13	0.08	8.7	10.0		15
52	San Fernando, 1971	Van Norman Inlet	6.4	33	13	0.15	15.8	15.5		15
53	San Fernando, 1971	Tehachapi-2	6.4	73	13	0.07	8.4	9.7		15
54	San Fernando, 1971	Tehachapi-3	6.4	73	13	0.07	8.4	9.7		15
55	San Fernando, 1971	Carley Porter	6.4	65	13	0.08	9.3	10.5		15
56	San Fernando, 1971	Van Norman North	6.4	23	13	0.19	19.8	18.3		15
57	San Fernando, 1971	Saugus	6.4	23	13	0.19	19.8	18.3		15
58		San Francisquito	6.4	24.5	13	0.18	19.1	17.8		15
59		Elizabeth	6.4	27.3	13	0.17	17.9	17.0		15
60		Antelope	6.4	37.5	13	0.13	14.4	14.5		15
61	Inyokern, 1946	Jawbone	6.3	26.0	15	0.16	16.8	15.7		
62		Jawbone	6.3	28.0	15	0.16	16.0	15.2		
63		Jawbone	6.3	31.0	15	0.14	15.0	14.4		
64		Freeman	6.3	22.0	15	0.18	18.5	16.9		
65	Arvin Tehachapi, 1952	Saugus	7.7	90.0	20	0.14	23.0	31.0		
66		San Francisquito	7.7	75.0	20	0.17	27.2	35.0		
67		Elizabeth	7.7	70.0	20	0.18	29.0	36.7		
68		Antelope	7.7	48.0	20	0.25	39.7	46.3		
69		Jawbone	7.7	90.0	20	0.14	23.0	31.0		
70	Chalone, 1922	Jawbone	6.1	52.0	20	0.08	8.5	8.9		
71		Freeman	6.1	52.0	20	0.08	8.5	8.9		

APPENDIX B — EFFECTS OF THE MARCH 1964 EARTHQUAKE ON WELLS OF THE ALASKA AREA

(Data Summarized from Reference 46)

No.[a]	Depth, meters	Diameter, meters	Water Level, meters (below land surface) Before	After	Earthquake Effects
1	19.8	0.1524			Water level dropped 7.6 m. Fissure nearby; pumped sand.
2	13.7	0.1524			Well went dry; drilled another well to 49 m.
3	19.5	0.1524	9.5	10.8	Water level probably fell at least 1.5 m.
4	45.7	0.2032	Flowing	Flowing	Unaffected.
5	22.2	0.1524			Unaffected.
6	14.9	0.1524	10.4		Reportedly went dry; was redrilled.
7	17.1	0.1524	2.6	2.3	Unaffected.
8	17.2	0.1524			Muddy for 1 day.
9	15.8	0.1524			Went dry and drilled to 37.5 m in 4-64 water level now 9.1 m.
10	37.2	0.1524	21.9		Unaffected.
11	41.4	0.1524	39.0		Went dry 3 weeks after quake. Deepened 4 m.
12	40.8	0.1524	13.6	17.6	Water level dropped at least 4 m.
13	138.1	0.2032	14.2	21.7	Water level dropped at least 7.6 m.
14	18.9	0.1524	7.6		Muddy for 1 day.
15	65.2	0.1524			Went dry about 1 month after quake. Deepened 3 m with less production than before quake.
16	64.9	0.1524	62.8		Went dry; recovery unknown.
17	30.5	0.1524	25.1		Muddy for about 1 week.
18	39.3	0.1524	25.9		Muddy for 2 days.
19	78.6	0.2032	1.5	7.0	Water level dropped about 5.8 m; still recovering (10-64).
20			Flowing		Lost artesian flow; has not returned.
21	106.4	0.1524	34.1	28.9	Water level rose and fell; now at 40 m (9-64).
22	41.1	0.0762	18.0		Muddy for 2 days.
23	97.5	0.1524	12.4	22.7	Water level rose and fell; still recovering at 16.4 m (9-64).
24	82.3	0.254	26.4	26.9	Unaffected.
25	54.9	0.254			Unaffected.

a. Well numbers refer to those on map in U. S. G. S. Professional Paper 544B.[46]

No.	Depth, meters	Diameter, meters	Water Level, meters (below land surface) Before	After	Earthquake Effects
26	50.3	0.1524			Pumped sand for 2 days. Water level unchanged.
27	50.3	0.1524	47.8		Went dry, possibly still dry.
28	59.4	0.1524	7.0		Muddy about 1 day.
29	87.2	0.1524	12.8		Went dry; came back about 1 month later.
30	62.8	0.1524	1		Pumped sand for 1 day or so.
31	27.4	0.1524	7.6		Muddy for undeterminable length of time.
32	19.2	0.1524			Unaffected.
33	148.1		Flowing	7.6	Water level dropped about 7.6 m. Completely recovered.
34	35.0	0.1524	1.2	3.6	Muddy for 2 days; water level dropped about 2.4 m.
35	14.0	0.1524	4.3		Pumped sand; strong odor for 1/2 day.
36	40.8	0.1524	4.1	4.6	Water level dropped at least 0.3 m.
37	30.5	0.1524	8.2	11.5	Water level dropped about 3 m; recovered 1.8 m.
38	69.5	0.2032	46.9		Unaffected.
39	61.0	0.1524	Flowing		Unaffected.
40	112.8	0.2032	37.4	36.9	Water level probably dropped; fast recovery.
41	14.8	0.1524	11.6		Muddy for 4 days.
42	16.8		12.2	11.5	May have dropped before recovering.
43	11.3	0.1524	9.1		Unaffected.
44	42.3	0.2032	5.6	7.7	May have dropped more than 2.1 m.
45	48.5	0.254	9.8		Unaffected.
46	68.6	0.2032	7.8	9.0	Dropped at least 1.2 m.
47	6.1	0.1524	2.4	2.8	Possibly dropped 0.46 m.
48	32.0	0.1524	7.1		Muddy for about 2 weeks; water level dropped slightly.
49	29.9	0.1524	7.1		Unaffected.
50	37.5	0.1524	5.8		Unaffected.
51	6.7	0.1524	1.5		Muddy for 2 days.
52	143.2	0.2032	23.0		Casing bent and broken.
53	45.4	0.1524	7.1		Unaffected.
54	64.0	0.2032	16.0	20.5	Dropped at least 4.6 m; maybe partly due to pumpage.

No.	Depth, meters	Diameter, meters	Water Level, meters (below land surface) Before	After	Earthquake Effects
55	69.2	0.1524			Unaffected.
56	95.4	0.1524	0.61		Muddy 2 days; production poor at low tides now.
57	32.3	0.1524	9.1		Muddy for 1 day.
58	47.8	0.2032	Flowing	Flowing	Muddy for 3 days.
59	39.6	0.1524	Flowing	Flowing	Unaffected.
60	30.2	0.1524	10.0		Muddiness cleared with pumping.
61	34.1	0.1524	4.6		Muddy for 2 days.
62	41.8	0.1524	39.9		Quite muddy for several days.
63	23.5	0.1524	Flowing		Reported to have been polluted by quake. Damaged casing (?).
64	9.4		8.5		Unaffected.
65	34.7	0.1524	18.1	19.9	May have dropped 1.5 m or more.
66	45.4	0.1524	6.0	7.2	Dropped at least 0.9 m.
67	36.6	0.1524	Flowing	7.1±	Flow lost and had to install pump.
68	16.2	0.1524	4.3		Muddy for about 1 week.
69	42.7	0.1524		24.4±	6.1 m of mud in casing. Pumped at 3.8 L/sec for 30 hour to clear.
70	26.8	0.1524	6.4		Water level fell (pump damaged).
71	32.0	0.1524	25.9(?)		Unaffected.
72	27.1	0.1524	7.9		Unaffected.
73	42.4	0.1524	21.4	26.0	Water level fell at least 3.0 m and perhaps 6.1 m.
74	11.0	0.1524	4.6	2.0	Muddy for unknown length of time.
75	53.6	0.1524			Unaffected.
76	32.9	0.1524	2.1		Unaffected.
77	10.0	0.1524	3.0		Had to redrill; now has "artesian" at 13.7 m.
78	14.6	0.1524	1.4		Unaffected.
79	15.5	0.1524	4.1	8.2	Minimum drop about 4.3 m.
80	30.5	0.1524	10.7		Unaffected.
81	54.2	0.1524	6.1		Unaffected.
82	14.6	0.1524	5.5		Muddy for 5 days.
83	64.3	0.2032	17.1	18.2	Possible drop of 1.2 m or more.
84	151.5	0.2032	13.2	19.1	Presumably fell minimum of 5.8 m; casing severely damaged. In the Turnagain Heights area.
85	31.1	0.1524	18.3		Water level fell and casing destroyed, near Turnagain Heights.

No.	Depth, meters	Diameter, meters	Water Level, meters (below land surface) Before	After	Earthquake Effects
86	24.1	0.1524	19.2	19.7	Probably unaffected.
87	31.7	0.1524	Flowing	Flowing	Unaffected.
88	16.4	0.1524	4.9		Very muddy for 3 days; reported odor.
89	24.7	0.1524	6.1		Muddy for many weeks; water level may have dropped.
90	4.9	4.9	2.4	2.3	Water level rose slightly; normal in one day.
91	70.7	0.1524	15.2		Unaffected.
92	123.7	0.2032	16.3	17.4	Probably dropped at least 0.91 m, possibly more.
93	92.9	0.1524	15.2		Unaffected.
94	112.8	4.9	18.6	21.3	Unaffected (?). Heavily pumped, water level down 2.7 m.
95	97.2	0.1524	17.0		Unaffected.
96	71.0	0.1524	18.3		Muddy for 1 day.
97	84.7	0.2032	12.2		Muddy for 1 day.
98	35.7	0.1016	3.0	3.8	Water level dropped about 0.91 m.
99	70.4	0.1524	2.4	8.3	Water level reported to have dropped 12.2 m.
100	164.6	0.254	47.2	50.3	Water level dropped about 3.0 m.
Valdez	7.3				Bent seaward by land movement; casing sheared 4.7 m below the surface.
Valdez					Damaged, possibly by electric failure.
Valdez					Unaffected.
Seward 4	∿30.5				Damaged; casing bent by earth movement.
Seward 5	∿30.5				Damaged; casing bent by movement of part of alluvial fan.
Seward 6	∿30.5				Survived quake; about 1 month later pump turbine jammed because of ground movement or settlement.

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